Tesserae on Venus: Evidence of Fluvial Erosion and Characterization of Lineaments

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Abstract

Tesserae are the stratigraphically oldest and geologically complex regions on Venus. Recent global climate models propose that Venus experienced Earth-like temperatures for most of its history prior to catastrophic global warming. This study tests for fluvial erosion prior to global warming by comparing valley patterns in tesserae with terrestrial stream patterns. Valleys were identified by margins of tesserae partially flooded by younger basaltic plains flows. Recognition of erosion in tesserae is a paradigm shift and has numerous implications. One such implication relates to the interpretation of lineaments sets in tesserae.

Multiple lineament sets are characteristic of tesserae and are typically interpreted as the surface trace of fold crests, faults and grabens. However, the interpretation of erosion allows additional interpretations of lineaments as the exposed edges of sedimentary or volcanic sequences. PCA (Principal Component Analysis) can be applied to curving lineaments to calculate dips for such planar geological units and structures.

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1. Chapter: Introduction

1.1 Planet Venus

Venus is commonly referred to as Earth's sister planet because of the proximity between these two planets in the solar system and their similarities in terms of size (Figure 1.1), mass, density, composition and gravity (Hoffman et al., 1980). However, Earth-based observations and various space missions to Venus, have revealed very different environments on the two bodies. Contrary to Earth, Venus exhibits a lack of plate tectonics, extreme surface temperatures ($\sim 450^{\circ}\text{C}$) and a surface atmospheric pressure of 9000 kPa (90 times that of Earth). This is largely due to a thick atmosphere composed of 96% CO_2 , lesser quantities of N_2 and H_2S and lastly a low-lying cloud layer of sulphuric acid droplets (Donahue and Russell, 1997; Chaisson and McMillan, 2010). These gases created a runaway greenhouse effect by trapping nearly all of the Sun's incoming radiation, in addition to any internal heat dissipated from the planetary interior. Before the Soviet Union began the Venera space missions in the early 1960's, existing knowledge of Venus' surface conditions and topography remained purely speculative. It was not until 1990's that the most detailed images of Venus were provided by NASA's 1990-1994 Magellan mission, which collected high resolution (75-100 m/pixel) images of 98% of the planet's surface using Synthetic Aperture Radar (SAR) (Young, 1990; Saunders et al., 1992; Saunders and Pettengill, 1991).

Figure 1.1: Comparison of Venus (shown on left, imaged using microwave spectrum) and Earth (shown on right, imaged using visible spectrum). Source: NASA/JPL.

Venus preserves an extensive history of basaltic intraplate magmatism (e.g. Ernst et al. 2007) consisting of: (1) individual volcanoes that are 100–1000 km in diameter and are interpreted to have a plume origin; (2) annular structures (termed coronae and arachnoids) with diameters averaging 300 km, that can have a diapir or plume origin; (3) radiating graben-fissure systems (including novae) caused by underlying laterally propagating dykes and extending up to 2000–6000 km away from the volcanoes or coronae located at their foci; (4) lava flow fields of scale comparable to terrestrial flood basalts; (5) regions of small shield volcanoes, often a few hundred kilometers across; and (6) canali which are narrow sinuous lava channels whose length can reach up to 7000 km. All these tectono-magmatic features are superimposed on earlier plains' volcanism and highly deformed “basement” terranes termed tesserae.

1.2 Tesserae

Tesserae, also known as complex ridge terrains, occupy approximately 8% of Venus' surface (Figure 1.2) and are commonly associated with elevated continent-like regions (crustal plateaus) (Figure 1.3) embayed by adjacent volcanic plains (Barsukov et al., 1986; Sukhanov, 1986, 1992; Bindschadler and Head, 1989; Solomon et al., 1992; Bindschadler et al., 1992a,b; Ivanov and Head, 1996a,b; Hansen and Willis, 1996; Pritchard et al., 1997; Head and Basilevsky, 1998; Campbell and Taylor, 2002; Bleamaster and Hansen, 2005; Romeo and Turcotte, 2008; Gilmore and Head, 2018). The age of tesserae has been estimated using the impact crater counting method as $(1.47 \pm 0.46) \times T$ where $T = 750$ Ma is the average age of the surface of Venus (Ivanov and Basilevsky, 1993; Basilevsky and Head 2002). Tesserae consist of at least two sets of intersecting lineaments (e.g. ridges and grooves) and are the result of tectonic deformation of a precursor terrain (Basilevsky and Head, 1998). The nature of that precursor terrain, as well as the causes and mechanisms of deformation are still under debate (Hansen and Willis, 1996; Gilmore and Head, 2018). Current topics of discussion regarding tesserae are: their extent (global vs regional), and the origin (downwelling vs upwelling) and composition (mafic vs felsic) of their precursor terrains.

Figure 1.2: Global distribution of tesserae on Venus (Ivanov and Head, 1996). Red box locates Salus Tessera, a key study area in this thesis. Yellow box locates Tellus Regio, discussed in Chapter 3. Location of Figures 3.7 and 3.8 are shown.

Figure 1.3: Global topography of Venus. Red regions represent areas of topographic highs and darker blue regions represent areas of topographic lows. Tesserae are generally associated with topographic highs (Bindschadler et al., 1992 a, b). Red box locates Salus Tessera, a key study area in this thesis. Yellow box locates Tellus Regio, discussed in Chapter 3. Image source: <http://ails.arc.nasa.gov/ails/?v=thumbs&st=1&so=unsorted&page=1&r=0&q=AC78-9135&x=0&y=0>.

Deformation structures seen on tessera mostly consist of normal faults, thrust faults, folding or a combination (Solomon et al., 1991). Large tesserae (e.g. Aphrodite Terra) commonly consist of sets of presumably contractional ridges and troughs that are crosscut by extensional fractures or grabens (Hansen, 2000). Some large tesserae also contain long, narrow, steep-sided depressions referred to as “ribbon structures” by some authors (Hansen and Willis, 1996; Hansen and Willis, 1998). They differ from grabens by possibly being bound by vertical or nearly vertical fractures rather than by the inward dipping faults seen in grabens (Hansen and Willis, 1998). However, a new model (Hanmer, 2020) suggests that ribbon structures can be interpreted as grabens overlying laterally propagating mafic dykes.

Multiple models have been put forth to explain the formation of tesserae (Solomon, 1993; Turcotte, 1993; Hansen et al., 2000; Romeo and Turcotte, 2008). Formation by mantle downwelling is the most currently accepted model (Gilmore et al., 1998) resulting in compression and thickening of the crust. In this model, compression is followed by isostatic rebound due to the thickening and delamination of the mantle lithosphere thus producing extensional features on tesserae (Gilmore et al., 1998). However, the resulting topography according to this model would suggest a domical shape instead of the flat-topped plateau observed (Romeo and Turcotte, 2008). Hansen (2006) rejected the downwelling model and proposed a new, catastrophic model where crustal plateaus were formed by huge lava ponds generated by massive mantle melting due to large bolide impacts on a thin ancient lithosphere. This model generates questions about whether large bodies can melt a large enough portion of the mantle to generate sufficient volumes of magma. (Ivanov and Melosh, 2003). More recent literature is suggesting tessera formation via lateral accretion of belts (Gilmore and Head, 2018). For instance, detailed analysis of Tellus Regio (Gilmore and Head,

2018) suggests the SW portions of the tessera were separated at some point by volcanic plains and subsequently accreted together during a compressional event. This is supported by the presence of an interior, an indenter and a ridge (Senske, 1999) within the tessera.

One fundamental assumption in the study of tesserae has been that the current hyper warm conditions (450°C) that are currently characteristic of Venus also applied during the time of tesserae formation. However, new climatic models (e.g. Way et al., 2016) suggest Earth-like conditions prevailed on Venus during tesserae time and that the climate transitioned to the hyper warm conditions as a result of runaway greenhouse warming associated with massive CO₂ release during later voluminous and widespread flood volcanism. A key test of this model is to investigate the tessera terrains in detail and consider evidence of erosion, which would be indicative of pre-global warming conditions.

1.3 Literature Review

1.3.1 Magellan Mission

NASA's Magellan spacecraft (Figure 1.4) was launched from the Kennedy Space Center in Florida on May 4th, 1989. It entered Venus' orbit on August 10th, 1990 and began mapping the Venusian surface using Synthetic Aperture Radar (SAR) imaging at a resolution of ~75-100 m/pixel (Saunders et al., 1992). Along with SAR images, the spacecraft was also used to measure the topographic relief, radar reflectivity, surface slope, radio-thermal emissivity as well as gravity (Tanaka et al., 1993). The first orbital cycle, which orbited for 8 months, captured 84% of the planet using left-looking radar. The incidence angle ranged from 16.5 degrees at the north pole to 45.7 degrees at periapsis. Immediately following cycle 1, cycle 2 (right-looking radar) mapped approximately 50% of the planet's surface. This second cycle

was focused in the southern-hemisphere and covered two major gaps in the previous cycle. The incidence angle was about 25 degrees from 75 N to 55 S latitude, and then decreased to 12.7 degrees at the south pole. The final cycle (cycle 3) which was left-looking, filled in many of the remaining gaps before the completion of the mission (Saunders et al., 1992). The incidence angle reached a maximum of 25.6 degrees at 15 N. Part of the cycle was geared towards coverage of Maxwell Montes, from 75 N to 20 N at incidence angles from 27 to 36 degrees. The Magellan mission mapped a combined total of 98% of the planet's surface. The spacecraft was commanded to plunge into the atmosphere to gather aerodynamic data, which brought the mission to its end as the spacecraft burned up.

The high-resolution radar images of the Venusian surface showed evidence of extensive mainly basaltic volcanism (covering 85% of the surface) and highland "continents" that include highly deformed structures known as tesserae (covering 8% of the surface). The mission also revealed a lack of erosion and plate tectonics.

Smooth: Radar signal reflects away from spacecraft, no reflections detected by receiver; image appears dark.

Rough: Radar signal scatters against rough or uneven surfaces, reflections detected by receiver; image appears bright.

Figure 1.4: Schematic diagram of the Magellan spacecraft (Top) Source: NASA/JPL. Diagram representing microwave radar pulses reflecting off various surfaces (Bottom) (Graff, 2016).

1.3.2 Geological Mapping

The publication of high-resolution Magellan SAR data by the United States Geological Survey (USGS) has allowed for the detailed mapping of various geological features seen on the Venusian surface. This ongoing process includes the global mapping project managed by the USGS, where the surface is subdivided into 62 quadrangles (Figure 1.5) that have or will be assigned to a scientist for detailed mapping. In addition, regional mapping has also occurred in parallel with the USGS global mapping project. For instance, quadrangle V-32 has been mapped by a member of the Carleton University Venus Working Group (Bethell et al. 2019). In addition, Ivanov and Head (2011) have produced a global geological map of Venus, briefly describing the different features seen on the surface and their implications.

Figure 1.5: Outline of 62 quadrangles subdividing the Venusian surface for detailed mapping (Scale: 1:5,000,000). Source: USGS/IAU.

1.3.3 Carleton University Venus Research Group

Over the past nearly two decades, there has been a team dedicated to mapping Venus at Carleton University. Research was initially focussed on graben fissure systems which on Venus represent the surface expression of underlying dyke swarms (Grosfils and Head, 1994a; Ernst et al., 1995b, 2001, 2003), and dyke swarms represent feeder systems to flood basalts (Ernst and Buchan, 1997a, b, 2001). Graben-fissures can be identified on SAR images as radar-bright lineaments and are commonly seen to exhibit radiating, linear and circumferential geometries (Ernst et al., 1995a,b, 2001, 2003; Ernst and Buchan, 2001; Studd et al., 2011; Grosfils et al., 2014; Lu, 2014; Graff et al., 2018). By combining regional distribution maps of graben-fissure system maps and a global geological map produced by Ivanov and Head (2011), this research aims to provide a better understanding of the planet's intraplate magmatic processes and evolution through time.

The Carleton University Venus Research Group mapped graben-fissure systems in Nephthys Mons Quadrangle (V-54) (Blair and Ernst, 2002), Guinevere Planitia and Beta Regio (Ernst et al., 2003), Ulfrun Regio (Studd et al., 2011), Idunn Mons and Mielikki Mons areas (Davey, 2012), the Mead Quadrangle (Lu, 2014), Parga Chasma (Graff et al., 2018) and in the Decerto corona/Kallisto Vallis volcanic centre (MacLellan and Ernst 2019). In recent years, the Group has expanded geologic mapping beyond graben-fissure systems, to include themes such as pit crater chains (Davey, 2012), rift systems (Graff et al. 2018), lava flow fields (Lee et al., 2019; MacLellan and Ernst 2019), fluvial erosion on tesserae (Khawja et al, 2019), and coroneae structures (Bethell et al., 2019). As mentioned above Bethell et al. (2019) has mapped the Alpha Regio quadrangle (V-32) of Venus.

1.4 Research Objectives and Structure of the Thesis

The overarching goal of this thesis project is to analyze tesserae in detail and explicitly consider, for the first time, the role of water erosion. This present research is divided into two major aspects: chapter 3 considers evidence for erosion in tesserae and chapter 4 expands the interpretation of lineaments sets that characterize tesserae in view of possible erosion and provides a method to calculate the orientation of planar geological features associated with lineaments.

Chapter 2: Provides an overview of the mapping methodology used in this thesis and Chapters 3 and 4 address the research objectives.

Chapter 3: Due to current high surface temperatures ($\sim 450^{\circ}\text{C}$), it is generally assumed that water erosion did not operate on Venus, and there is abundant evidence for widespread volcanic resurfacing unaffected by erosion. Evidence for the absence of erosion includes features such as flow fields (Magee and Head, 2001) which exhibit simple superimposition of flow units, preservation of the surface expression of widespread shallow thrust faults called wrinkle ridges (Solomon et al., 1999), graben-fissure systems (Grosfils and Head, 1994), and lava channels (Oshigami et al., 2009). However, recent global circulation models (Way et al., 2016; Kane et al., 2019) have suggested the possibility of Earth-like climatic conditions on Venus for much of its earlier history prior to runaway greenhouse warming, suggesting fluvial erosion during tesserae time. Chapter 3 focuses on tesserae margins that were partially flooded by younger lava flows, where volcanic flooding provides a locally consistent horizontal surface, used to distinguish elevated peaks and ridges from valleys.

Evidence of erosion of tesserae provides evidence to support climate models suggesting a cool, wet climate on early Venus.

Chapter 4: Tesserae are characterized by a complex pattern of families of lineaments which can be straight or curved. They are generally interpreted as representing the surface trace of tectonic structures such as fissures, fractures, grabens, and fold crests. Single lineaments can represent fractures (also fissures and graben) that are expected to appear as thin, and straight or anastomosing lines. Single lineaments can also represent fold crests, which are expected to be wide, and straight or curved. Fractures are typically marked by a sharp zone of radar brightness and overall high contrast with surrounding areas, whereas folds are radar bright along one side and have a gradual brightness transition across them. Building on the evidence for erosion developed in Chapter 3 then the range of interpretations for these lineament sets can be expanded to include shallow dipping sequences of flood basalts, and sedimentary sequences that have been differentially affected by erosion. As a contribution to this expanded analysis of lineament patterns in tesserae, this study also introduces principal component analysis as a methodology to calculate strike and dip of these types of planar features associated with lineaments.

Chapter 5: This chapter summarizes the main findings in Chapters 3 and 4 and suggests avenues for future research.

2. Chapter: Methodology and Study Area

2.1 Magellan Data

All SAR images used in this research were obtained from the Magellan Mission and were collected and organized by the USGS (<https://astrocloud.wr.usgs.gov>), providing the base-maps needed for the detailed analysis of tesserae. Raw SAR images were processed from individual orbital cycles into strips known as F-BIDRs (full resolution basic image data records), which were then assembled to create F-MIDRs (full resolution mosaicked image data records). FMAPS (full resolution radar maps) were released by the USGS at a resolution of 75-100 m/pixel which includes coverage of both left-looking and right-looking radar profiles from all three mapping cycles. The intensity (radar bright vs radar dark) of a pixel is determined by the amount of reflectance and is a function of surface roughness and orientation with respect to the transmitter. Radar bright images represent rough surfaces, or surfaces facing the spacecraft receiver, while radar dark images represent surfaces composed of smooth material (Figure 1.4).

The Global Topographic Data Record (GTDR) (e.g. Figure 1.3), also known as the Magellan Global Topography, was released in 1997 using radar altimetry measurements. These data have a horizontal resolution of 10-20 km and vertical resolution of 50-100 m (Ford and Pettengill, 1992). A new set of higher resolution topographic data was developed by Herrick et al. (2012), using Magellan SAR stereo-derived data (Figure 2.1), produced by combining cycle 1 and cycle 3 data. This resulted in a topographic dataset with a 1-2 km horizontal resolution which allows for detailed interpretations and modelling on regions that exhibit complex deformation (e.g. tesserae). Unfortunately, the new data set is constrained by the

limited coverage from cycle 3 of the Magellan mission (20% of the planet) and the data gaps are filled in using gridded Magellan original altimetry.

Figure 2.1: Global coverage of the stereo-derived topography (combined Cycles 1 and 3) overlain onto Magellan SAR imagery (Cycle 1). Data are represented with colour coded elevation (e.g. top right image) and are elevation values are quoted relative to the mean planetary radius. Source: Herrick et al. (2012).

2.2 Mapping and Imaging Software

2.2.1 ArcGIS

Mapping of tesserae (extensional features, compressional features, flooded areas, folds, etc.) was completed using ArcGIS v10.6 software (<https://desktop.arcgis.com/en/arcmap/>). All basemaps imported into the program were downloaded in a sinusoidal map projection where each raster was georeferenced using the 'GCS Venus' coordinate system. The ArcCatalog function allows for the creation of editable layers known as shapefiles, useful for tracing out the detailed radar-bright linework corresponding to lineaments.

2.2.2 JMARS

JMARS (java mission-planning and analysis for remote sensing) is an essential GIS software used for viewing and analyzing remote sensing data from a variety of sources. Developed by Arizona State University's Mars Space Flight Facility, JMARS was made publicly available in 2003 after the addition of mission data products from other planetary bodies including Earth, the Moon, Mercury, Jupiter, Saturn (and their moons), selected asteroids and Venus, the focus of this research. The Venus datasets available on JMARS include Magellan SAR FMAP left/right/stereo mosaics at the resolution of 75-100 m/pixel, elevation (meters), shaded relief, slope and stereo-derived topography. The allotment of readily available scientific data, customizable spatial analyst features, and import/export capabilities made JMARS a valuable tool throughout the study, particularly for reconnaissance observations. JMARS was also used to create the topographic profiles across and along lineament sets in Chapter 4 and from which the orientation of planar features associated with lineaments sets was calculated.

2.2.3 Corel Draw

Corel Draw is a graphics editor that was used to format final figures, tables and graphs. The “outline trace” tool was used as a helpful visualization method that involved grouping pixel intensities from SAR images into multiple discrete bins and generating a map that provides improved resolution of lineament trends in tesserae.

2.2.4 XLSTAT

XLSTAT is a powerful statistical analysis tool that can be added to Microsoft Excel. It can be used to analyze, customize and solve over 220 statistical problems in an efficient and user-friendly way. XLSTAT was used to conduct principal component analyses (PCA) to determine dip of planar features associated with surface lineaments on tesserae (Chapter 4).

2.3 Study Area

Chapter 3 incorporates images of tesserae from across Venus, but Chapter 4 focusses on a particular tessera, Salus, which lies between 42° to 56° latitude and 2° to -8° longitude, along the boundary between the Scarpellini (V-33) and Mead (V-21) quadrangles. This small tessera which has a center latitude and longitude of 48.5° and -1.5°, respectively, and spans 850 km in diameter, is the focus of detailed lineament analysis in Chapter 4. It is also used as one of the examples for erosional features in Chapter 3.

Figure 2.2 SAR image of Salus Tessera. Location shown in Figures 1.2 and 1.3. The locations (labelled lines) for the topographic profiles shown in chapter 4.

3. Chapter: Fluvial Erosion on Venus

3.1 Introduction

There is some evidence for surface mineralogical changes due to weathering in the VIRTIS (Visual and Infra-red Thermal Imaging Spectrometer) data from the (2005 – 2014) Venus Express spacecraft (e.g. Smrekar et al. 2010). However, it is generally accepted that the surface of Venus does not display evidence for extensive erosion, which is convincingly true for stratigraphically younger lobate flows which exhibit simple superposition of flow units and have radar backscatter properties consistent with primary flow morphology and rheology (Byrnes and Crown, 2002; Zimbelam, 2003). Additional features such as shallow thrust faults called wrinkle ridges (Solomon et al., 1999; Bethell et al., 2020), graben-fissure systems (Ernst et al., 2003), and lava channels (including canali and sinuous rilles) (Bray et al., 2007; Oshigami et al., 2009) all have surface topographic signatures that would have been lost if fluvial erosional processes had been active. Impact craters are mostly pristine except where partially flooded by later lavas (Whitten and Campbell, 2016). These observations imply a lack of hydrological erosion on Venus, consistent with the planet's current high surface temperature of 450 C.

3.2 Erosion on Venus

There are 4 major reasons to expect erosional features in the stratigraphically oldest preserved units on Venus, tesserae:

- 1) The assumption of the absence of erosion in the tesserae needs to be questioned in light of recent climatic modelling of Venus which suggest that Earth-like conditions could have

been present for most of Venus history but that a runaway greenhouse effect changed Venus' climate catastrophically and led to loss of water (Ingersoll, 1969; Way et al., 2016; Kane et al., 2019; Way et al., 2020). The cause of this greenhouse effect is linked to catastrophic CO₂ degassing during global volcanic resurfacing. Under the volcanic interpretation, the timing of the climatic transition would correlate with the onset of major volcanic resurfacing at approximately 700 Ma. Therefore, the stratigraphically earlier tesserae might thus have formed under climatic conditions, where liquid water was present, allowing for the possibility of fluvial erosion.

2) The tectonic complexity of tesserae (e.g., Hansen and Willis, 1996), including evidence of accretion tectonics (Gilmore and Head, 2018) suggests deformation at depth followed by unroofing and exposure at the surface (Ernst et al., 2019). However, this hypothesis remains to be tested by modeling the deformation of mafic and felsic units under a range of atmospheric pressure and temperature conditions relevant to Venus.

3) Lineaments with irregular curvilinear patterns in tesserae may be indicative of shallow-dipping planar layers that follow undulating topography caused by erosion (e.g. in Alpha Regio) (Byrne et al., 2019, Byrne et al., 2020; Khawja et al., 2020 and Ernst et al., 2020). By analogy with Earth, such shallow-dipping layers could be a sequence of volcanics (i.e., flood basalts, rhyolites, or pyroclastics) and/or represent sedimentary units, or perhaps even layered intrusions.

4) Present-day topographic variations observed in tesserae can be interpreted as due to water erosion (Ernst et al., 2019; Khawja et al., 2020; Ernst et al., 2020).

This Chapter focuses on the fourth point by addressing the causes of observed topographic variations in tesserae. This Chapter first addresses whether the variations can be due to primary topographic variations due to folding or faulting. Once concluding that erosion is required, the presence of water, wind and/or glacial erosion are assessed.

3.3 Topographic Variations

In a search for features indicative of erosion it is necessary to consider the scale of relevant topographic features vs the resolution of the topographic data.

Figure 3.1 shows a topographic profile across Tellus Regio where, across distances of many hundreds of kilometres there are topographic variations up to three kilometres. Most dramatically, the Western Margin and Eastern Margin terranes are higher and interpreted as thrust belts onto an older crustal block. Thus, there are major topographic changes of up to several kilometres that can represent terrane accretion tectonics (Gilmore and Head, 2018). On this large scale, it is also possible to envision tectonic unroofing along faults that bring deeper deformed units upward and then exposes them by erosion. However, the effect of erosion to modify the structures produced by accretion tectonics was not discussed by Gilmore and Head (2018). On the much more local horizontal scale of a few tens of kilometres, the topographic variations are often less than 100 m. It is this more local-scale small-magnitude topographic variations that are the focus of this Chapter.

Figure 3.1: Top: east-west topographic profile of Tellus Regio. Western and eastern margins of Tellus Regio (red boxes) may represent terranes that have been accreted and uplifted (Gilmore and Head, 2018) and then subsequently eroded (suggested herein). Bottom: SAR image of Tellus Regio with the trace of topographic profile A to A' (orange line) shown on top. Location on global map is shown in Figures 1.2 and 1.3.

3.4 Methodology for Identifying Topographic Valleys

The scale of the expected topographic variations of tens to hundreds of metres is similar to the resolution of the Magellan data, which (as noted in Chapter 2) has poor vertical and horizontal resolutions of 50-100 m and $\sim 10 - 20$ km ('footprint'), respectively. The new higher resolution stereo topographic maps recently produced from combining Cycle 1 and Cycle 3 Magellan SAR data (Herrick et al., 2012), have a similar vertical resolution but an improved horizontal resolution of 1-2 km. The vertical uncertainties of 50-100 m could be small enough for topographic analysis. However, since the horizontal footprint for this elevation estimate is 1-2 km at best (with the new Herrick et al. (2012) reprocessed data) and at worst, 10-20 km (original Magellan topographic data), it is impossible to uniquely match topography values to distinct features in the Magellan images (which have a 75-100 m pixel resolution). This problem is less severe for the smooth plains areas of Venus where the topography is gently-varying, but is acute for the topographically rough tesserae.

To circumvent the issue of elevation uncertainties, this research applies a technique of only using portions of tesserae that are partially flooded by younger mafic lava flows (Figure 3.2). It is assumed that lavas have flooded these areas to approximately the same level. Therefore, the lava flooding represents a horizontal datum, that clearly identifies the highest peaks and ridges, and distinguishes these from the "valleys" filled by lava flooding. The pattern of the identified valleys can be diagnostic of earlier fluvial erosion processes.

Figure 3.2: LEFT: Magellan SAR image (central coordinates: 61.7E, 6.5S) showing segments of tesserae (light grey) surrounded by plains unit (dark grey). RIGHT: Schematic diagram of tessera terrain (Tt) flooded by lava flows of plains unit (Ps).

To further illustrate the effectiveness of this approach to improve topographic resolution, some terrestrial analogues of ‘flooding’ of topographic low areas are considered. It can be observed that flooded fjords, nunataks and yardangs appear morphologically similar to tesserae margins partially flooded by lava flow—with water as the datum (for flooded fjords), ice as the datum (for nunataks), and sand as the datum (for yardangs) (Figure 3.3). In each of these examples the geological features above the datum are rendered especially prominent.

Figure 3.3: Topographic highs emerge above a lower, relatively smooth, datum. A) Magellan left-look SAR image from Venus at 6.5°S, 61.7°E (central coordinates) showing portions of tesserae (light grey) surrounded by plains units (dark grey). B) Fjords flooded by water in Nain, Labrador, Canada (Source: Google maps) (56.5°N, 61.7°E) C) Nunataks (high standing mountains) surrounded by a field of ice and snow (65.4°N, 37.3°W) <https://commons.wikimedia.org/wiki/File:Eastcoastgreenland1.jpg>. D) Yardang field bordering the desert of Kumtagh, China (42.7°N, 90.3°E)³, with individual features that are hundreds of metres long.

3.5 Primary Topography vs Erosion

In the traditional interpretation of tessera, i.e. in the absence of erosion, the present tesserae surface should only reflect primary topography produced by folding and faulting. Four models are considered when explaining topographic variations in tesserae (Figure 3.4). The first three models explain topography as primary, i.e. only caused by folding or faulting, without any subsequent erosion. The fourth model (Figure 3.4D) requires erosion.

Figure 3.4: Schematic diagrams of three topographic models to explain topographic variations: faulting (normal (A)/thrust (B)), folding (C) and erosion by river/glacier or wind (D). T = tessera, L = lava flooding, M = mass wasting, R = river erosion, G = glacial erosion, Z = zeugens, Y = yardangs.

Figure 3.5: Magellan SAR image (61.7E, 6.5S) showing segments of tesserae (light grey) surrounded by plains unit (dark grey). Left: tectonic interpretation. Right: stream erosion interpretation (black lines represent interpreted stream valleys later filled by lava flows). After Khawja et al. (2020).

Figure 3.6: a) Left looking Cycle 1 Magellan SAR image (central coordinates 4.4°S, 48.2°E) from the southern part of Salus Tessera, showing a re-entrant (arrow) that has been flooded by younger plains lavas (dark grey). Alternative explanations for cross section A-A': synformal folding (b) erosion (c). Both models (tectonic and erosion) are shown in (d) and (e). Parts (d) and (e) after Khawja et al. (2020).

Figure 3.5 shows an irregular pattern of tesserae high ground and valleys (marked by lava flooding). In this case, the E-W linear structures on the tesserae tend to be locally oblique to the trend of possible grabens and horsts, and erosion may offer a simpler interpretation.

Eight additional examples of partially flooded tesserae are considered in terms of both purely tectonic and erosional interpretations (Figures 3.6, 3.7 and 3.8). From this perspective, the tessera valley pattern in the first example (Figures 3.7a and 3.6) can be interpreted as a broad synformal flexural fold with a wavelength of 120 km. However, in such a folding model, the adjacent anticlinal portions should exhibit no structures (or perhaps only minor parasitic folds and secondary structures) in the absence of erosion (Figure. 3.6b) which seems at odds with their apparent tectonic complexity. Another structural alternative would be a down-dropped NNE-SSW-trending central block with a width of 30-50 km. The volcanic-flooding pattern, however, does not clearly delineate a simple down-dropped block, and there is no obvious continuation of postulated rift margin structures outside the area of volcanic flooding to the NNE (and such features should be obvious in the absence of erosion). An alternative interpretation is an initial down-dropped block followed by a protracted history of erosion in the direction of the arrow producing a wide valley (Figure 3.6a). Figure 3.7C could be interpreted as a series of parallel graben or as an anticlinal-synclinal sequence with a spacing of 4-10 km. Figure. 3.7D is more difficult to explain structurally but has some resemblance to “chocolate tablet boudinage” structures (Ghosh, 1998). In each of the four examples presented in Figure. 3.7, there are additional generations of superimposed lineaments and surficial irregularities that would require multiple generations of tectonism down to the scale of image resolution (100 m/pixel). On the other hand, adding erosion to

such primary tectonic processes could provide a simpler explanation for many of the topographic complexities.

In summary, tesserae which have been partially flooded by lava flows, exhibit patterns of elevated areas (peaks and ridges) and valley (flooded areas) which at best be only partially explained by primary features (folding and faulting) and there must be a considerable erosion component. The following section examines the stream drainage pattern story to assess the role of water erosion, and the possibility of glacial and wind erosion are considered in sections 3.7 and 3.8.

Figure 3.7: Tesserae regions that are partially flooded by mafic flows in interpreted terms of stream drainage patterns. Each row features a Magellan SAR image (centre) on which an interpreted valley pattern is drawn based on the pattern of volcanic flooding (right) and which is approximately matched to major types of terrestrial stream drainage patterns (left). Types of stream patterns on Earth are after Howard (1967) and Bridge and Demicco (2008). Centre locations of SAR images: rows a (4.4°S , 48.2°E), b (16.3°S , 57.3°E), c (4.6°S , 62.1°E) and d (7.5°S , 68.8°E). The SAR images are left-looking Cycle 1 from the Magellan mission; black rectangles are gaps in the data. In each image north is to the top. Locations are shown in Figure 1.2.

Figure 3.8. Additional examples of tesserae regions that are partially flooded by mafic flows in terms of stream drainage patterns. Each row features a Magellan SAR image (centre) on which an interpreted valley pattern is drawn based on the pattern of volcanic flooding (right) and which is approximately matched to major types of terrestrial stream drainage patterns (left). Types of stream patterns on Earth are after Howard (1967) and Bridge and Demicco (2008). Centre locations of SAR images: rows a (74.4° E, 4.6° S), b (69.8° E, 1.1° S), c (129.0° E, 50.8° N) and d (126.4° E, 48.9° N). The SAR images are left-looking Cycle 1 from the Magellan mission; black rectangles are gaps in the data. In each image north is to the top. Locations are shown in Figure 1.2.

3.6 Water Erosion

3.6.1 Comparison with Stream Drainage Patterns

The valley patterns of the eight tesserae shown in Figures 3.7 and 3.8 are compared with terrestrial stream drainage patterns (Bridge and Demicco, 2008). Notably, the tessera valley patterns are morphologically similar to five of the six recognised terrestrial stream drainage patterns: “trellis”, “radial”, “parallel”, “dendritic” and “rectangular” (the additional pattern that is not recognised in these tessera examples is the “annular” pattern). The morphological and dimensional similarity between these tessera valley patterns and terrestrial stream drainage patterns are consistent with a scenario under which fluvial erosion contributed to shaping tessera topography.

Terrestrial stream systems can be quantified in terms of width, length, changes in orientation, sinuosity, spacing, degree of interconnectivity, etc. Such data for Venus tessera valleys would enhance the comparison with terrestrial stream systems. However, the width of lava flooding in the valleys (up to >50 km) should not be interpreted as the width of the postulated stream systems. Depending on their accumulated thickness, the infilling flows could extend up the sides of the valleys, thus obscuring the details of the fluvial system beneath, including evidence of a protracted fluvial history.

3.6.2 Tear Drop Shaped Island

A further example of fluvial erosion is offered in Figure. 3.9 where a tear-drop-shaped “island” is apparent in a lava-flooded valley within a tessera. The tear-drop geometry suggests flow from west to east. An interpretation in which the lava flow causes the

distinctive shape is unlikely since the lava flow was likely emplaced from east to west from the adjacent volcanic plains. On the other hand, the interpretation of flow from west to east would be consistent with a stream system eroding material from the interior of the tessera.

Figure 3.9. Tessera showing a tear-drop-shaped “island” (16.7°S, 058.2°E) Centre of image is at 16.7°S, 058.0°E. North is to the top. For location in a broader context see red box in Figure. 3.7B

Wind and ice erosion are next considered.

3.7 Wind Erosion

Present-day conditions on Venus do not allow for the existence of liquid water or ice, thus wind erosion is the dominant current style of erosion on the planet. There are two classes of aeolian features in volcanic areas of Venus: depositional and erosional.

Depositional features include parabolic halos, wind streaks, dunes and ergs (dune fields at least 125 km², (Parrish 2001)). The halos represent impact ejecta material that has been deposited downwind from an impact crater in a parabolic pattern (Ivanov et al., 1992). At least two ergs have been recognized during the Magellan mission: the Aglaonice dune field, which covers approximately 1,290 km² and the Meshkenet dune field (17,120 km²) (Greeley et al., 1992). These seem to be mostly transverse dune fields (with dune crests perpendicular

to prevailing winds). Despite the many differences in atmospheric conditions between the two sister planets, Venus uses the same mode of wind transportation as Earth (Craddock, 2011) therefore suggesting the dunes have a sand-dominant composition.

From among types of wind erosional features observed on Earth (ventifacts, rock pedestals, zeugen and yardangs) (Figure 3.10), only yardangs have so far been observed on Venus. One example is concentrated in an area 300 km southeast of Mead crater and average 25 km long and 0.5 km wide (Greeley et al., 1992). These features can be distinguished from wind streaks by having well defined boundaries and not originating from (being downwind from) topographic features. The presence of these yardangs suggests the presence of movable deposits that have been eroded over time and indicate wind erosion mechanisms are currently still active and have been active in the past (Basilevsky and McGill, 2007).

Figure 3.10: Examples of ventifact (A), rock pedestal (B), zeugen (C) and yardangs (D). Source: <http://www.yourarticlelibrary.com/geology/wind-erosion/6-main-features-of-wind-erosion-geology/91192>

Yardangs are formed in environments that have strong uni-directional winds that cut down low lying areas into parallel ridges which gradually erode into individual hills. They are commonly created from softer rock types such as siltstone, sandstone, shale and limestone but are also observed in schist and gneiss (Goudie, 2007). Given the uncertainties in the topography measurements, it is not possible to assess the height of the observed yarding on Venus. However, given the similarity in appearance and style of dunes, it can be inferred that their geometry is similar Earth. Yardangs on Earth (and other terrestrial planets), are divided into three major categories: mega-yardangs (several kilometers long

and hundreds of meters high), meso-yardangs (few meters high and 10 to 15 meters long) and micro-yardangs (few centimeters high) (Dong et al., 2016).

Zuegens are similar to yardangs but can be distinguished from wind streaks by having well-defined boundaries and not originating (i.e., being situated downwind) from topographic features. Although yardangs have been reported in the post-tessera volcanic regions, the important question is whether such wind erosional features could explain the topographic variations in tesserae. In terms of appearance both yardangs and zeugens tend to be parallel and elongated, so these wind erosional features could only explain those patterns where the valleys (and ridges between them) are linear (e.g. Figure 3.7C, 3.8A and 3.8B,). Figures 3.7A, 3.7B, 3.7D, 3.8C, and 3.8D do not exhibit parallel ridges and thus are unlikely to have been shaped by wind.

3.8 Glacial Erosion

Glacial features have not previously been observed on Venus and can not occur under current hyper-warm temperatures. However, glaciers would be possible if Venus was previously home to cooler temperatures. As noted in Way et al. (2016) climatic conditions (700 Ma ago) on Venus would be favourable for free water. This would imply that there could be lower temperatures at high elevations at that time or transient sub-zero conditions that would allow for the possibility of snow and ice. As a result, any evidence for processes of glacial erosion should also be considered for tesserae on Venus.

Figure 3.11: Glacial landforms created as a result of erosion. Major landform types include: cirque (starting location of a glacier), arete (narrow ridge crated by two joining cirques), horn (three or more glacially eroded aretes), tarn (mountain lake formed in a cirque dug out by a glacier), pater noster lakes (a glacial lake connected by a single stream or braided stream system), hanging valley (valley cut across by deeper valley or cliff), U-shaped valley (results from glacier moving through valley), ribbon lakes (long, narrow lakes found in glaciated U-shaped valleys) and fjords (U-shaped valley filled with melting glacier water) (Tarbuck and Lutgens, 1998; Bennett and Glasser, 2011).

There are several erosional features that are formed due to glacial processes (Figure 3.11). Unfortunately, the features are impossible to recognize in the Magellan images of Venus given the poor vertical and horizontal resolution in topography. Features such as cirques and hanging valleys will be present in the high standing areas (peaks and ridges), but it is not possible to resolve the fine scale topography which would be essential to reveal a glacial origin in these upland areas. Also, the subsequent lava flooding of the valleys would obscure any recognition of U-shape valleys (diagnostic of glaciers) vs V-shape valleys (more diagnostic of fluvial erosion). Identification of glacial features on Venus will have to await higher resolution data from a future mission.

3.9 Implications of Fluvial Erosion Interpretation

The prospect of fluvial erosion in tesserae provides a new interpretative framework for this important but enigmatic terrain type on Venus; two implications are discussed below.

3.9.1 Linking stream drainage pattern with underlying geology.

Terrestrial stream drainage patterns are controlled by rock properties and slopes (Bridge and Demicco, 2008) and thus the type of stream valley network that best fits a particular tessera could be indicative of local geology. As a generalization, radial, parallel and dendritic patterns are formed on slopes underlain by homogenous material. Trellis and rectangular patterns can be caused by dipping sedimentary strata of unequal resistance to erosion, by dipping volcanic flows with differential erosion between the upper and lower portions of a flow, and/or by orthogonal pre-existing fracture patterns. Radial patterns develop on topographic domes or basins composed of homogenous material. More specifically, with respect to the tesserae valley patterns in Figures 3.7 and 3.8, the following geological interpretations can be offered. The pattern in Figure 3.7A (and Figure 3.6) is consistent with a NNE-SSW-trending aulacogen-like structure (a failed arm of a triple junction rift system) that has been smoothed by erosion (removing the trace of any bounding normal faults) with incision along weak orthogonal (NW-SE trending) features (possibly dykes or a tilted section of a sill complex or a volcano-sedimentary sequence). Figure 3.7B is consistent with streams converging on a sedimentary basin with potential outflow to the NW or SE. Figure 3.7C is consistent with an E-W-trending horst and graben rift zone with superimposed erosion. Figure 3.7D is consistent with erosion affecting a geologically complex terrain. Building on the initial insights here, a global study of partially-flooded tesserae at a variety of latitudes

and altitudes, and their interpretation in terms of stream drainage pattern types could provide global a reconnaissance-level geological interpretation of tesserae.

3.9.2 Allowing simplified interpretation of lineament patterns in tesserae

Tesserae are characterized by complex lineament patterns, which can be irregular and/or curvilinear. A fluvial erosion model offers the possibility that such patterns reflect shallow-dipping planar layers of sediments or volcanic sequences that have been differentially eroded (Byrne et al., 2019, Byrne et al., 2020; Khawja et al., 2019, Khawja et al., 2020). This aspect is evaluated further in Chapter 4.

3.10 Conclusion

Partial lava flooding along the margins of tesserae are used as a local datum to reveal the pattern of local topographic highs (peaks and ridges) versus “valleys”. These patterns are considered against the default model in which no erosion was considered and therefore all topography could only be due to primary folds and faults. The complexity of tesserae are more simply explained if primary tectonics processes are combined with erosion.

The role of water, wind, glacial erosion are considered. The scale of wind erosion on Earth would not be sufficient to explain the erosional patterns on Venus. The topographic resolution of Venusian topography is not sufficient to recognize the essential features of glacial erosion (U-shaped valleys, cirques, hanging valleys) on the upland areas. On the other hand, water erosion can produce the appropriate “valley” patterns and thus represents a viable explanation for local topographic variation in tesserae on Venus.

The following Chapter discusses implications for the interpretation of lineaments sets in tesserae arising from the recognition of erosion.

4. Chapter: Influence of Erosion on Tesserae Lineaments

4.1 Introduction

This Chapter addresses interpretations of observed lineament sets in tesserae and includes the additional options that arise from including the possibility of erosion having occurred (Chapter 3). This contrasts with previous studies of tesserae lineament sets that do not consider the possibility of erosion. Topographic profiles that are both parallel and perpendicular to lineament sets are presented in order to document the degree of topographic variation along and across lineament sets. The interpretations discussed herein assume that lineaments are the surface trace of planar tectonic and/or geological features. This study also introduces principal component analysis (PCA) as a methodology to calculate the orientation of planar surfaces which due to differential erosion can exhibit curved surface traces (lineaments) if the planar feature is non vertical.

Figure 4.1: Lineaments interpreted as fold crests in eastern Ovda Regio (Ghent and Hansen, 1999). Original SAR image (top left) and annotated version (top right).

4.1.1 Lineaments on Tesserae

Lineament sets on tesserae (imaged by SAR) are generally interpreted in the current literature as representing tectonic structures (Figures 4.1 and 4.2) of various types including fractures, grabens, open tensile fractures, ‘ribbons’ and narrow fold crests. Gilmore et al. (1998) debated whether specific lineaments within tessera were grabens (bounded by faults dipping $\sim 60^\circ$) or open tensile fractures (dipping $\sim 90^\circ$). The term “ribbon” has been applied to symmetrical, steep-sided, graben-like structures generated by extensional forces (Hansen, 2018; Gilmore and Head, 2018). However, it is difficult to differentiate between ribbons and grabens given current resolution of SAR images. Hanmer (2020) proposed that the ribbons seen on tesserae represent grabens above dykes, similar to the interpretation for many grabens found in younger volcanic areas (e.g. Grosfils and Head, 1994). Some lineaments have also been interpreted as fold crests (Figure 4.1) (e.g. Hansen, 1997) which can be wide, straight or curved. Hansen (1997) notes that folds are radar bright along one side, have a

gradual brightness transition across them, and can be distinguished from fractures which are typically marked by a sharp zone of radar brightness and overall high contrast with surrounding areas.

If tesserae experienced erosion (Chapter 3), then additional interpretations are possible. For instance, lineaments can represent the surface trace of primary igneous or sedimentary layering that has been tilted and eroded. In particular, curved lineament sets can represent planar feature layers eroded differentially. Figure 4.3 illustrates the broad range of lineament interpretations in tesserae.

Figure 4.2: Portions of Salus Tessera (Figure 2.2) with superimposed topographic profiles. Minimum topographic uncertainties are provided for each profile based on a horizontal topographic footprint of 10 km and a vertical uncertainty of 50 m. Topographic profile data are extracted from JMARS. Profile location are shown in Figure 4.2.

Table 4.1: Average slope calculated for each profile in Figure 4.2

PROFILE	Point 1 (distance, km)	Point 1 (elevation, m)	Point 2 (distance, km)	Point 2 (elevation, m)	Slope (degrees)
a	5	1460	30	1650	0.44
b	5	1800	30	1450	0.80
c	5	2050	35	1500	1.05
d	5	1150	40	950	0.33
e	5	670	40	685	0.02
f	15	1900	40	1850	0.11
g	10	1290	60	1300	0.01
h	5	1620	25	2000	1.09
i	10	650	50	2000	1.93

a

b

c

d

Figure 4.3: Block diagrams representing the surface trace (lineaments) corresponding to different types of sub-surface tectonic and geological features: a) a thrust fault, b) sedimentary bedding or volcanic flows, c) grabens and d) strike-slip faults.

Basic geological features could be recognized as lineaments in tesserae in several ways. Thrust faults could appear as widely spaced lineaments that have shallow to steep dips, which would reflect the listric geometry of such faults (Figure 4.3a). Sedimentary and volcanic sequences would typically appear as narrow spaced lineaments that are subhorizontal or tilted if there is some deformation (Figure 4.3b). On the other hand, subvertical geological features can range from narrow to widely spaced lineaments, and can include normal faults, strike-slip faults (Figure 4.3d), dykes and their overlying graben (Figure 4.3c). Any subsequent block tilting or folding would change the dip of planar features.

Figure 4.4: Illustration of the Rule of V's (Lisle, 2003).

The possibility of erosion (Chapter 3) can provide constraints on the dip of layers. Differential erosion causes surface lineaments of planar features to curve. For instance, according to the 'Rule of V's' the presence of erosional valleys causes apparent curving of surface lineament traces up- or down-stream depending on the dip of the planar features (Figure 4.4). On the other hand, straight lineaments may represent vertical planar surfaces across any topography. Straight lineaments can also represent planar surfaces of any dip as long as the strike of the plane is along a line of constant elevation. For lineaments that represent fold structures, the effect of erosion is shown in Figure 4.5. If there is no erosion, the fold crest is represented by simple straight lineaments. However, erosion would progressively remove the fold crest, and lead to a pair of lineaments marking the boundaries between folded units (Figure 4.5).

Figure 4.5: Lineament expressions due to folding (a) and erosion (b).

4.1.2 Topographic Profiles

Topographic profiles were generated across portions of Salus Tessera (Figure 4.2). These were aligned parallel and/or perpendicular to dominant lineament trends. There were

several goals of this exercise: A) To assess the topographic variation; B) Identify changes in topography that could be associated with obvious features in the SAR image (e.g. faults); and C) Provide constraints on layer spacing based on lineament spacing and topography.

A) The magnitude of topographic variation differs throughout the various profiles (Figure 4.2 a-i). Profiles c and i vary in topography significantly (1000 m and greater), whereas profiles f and g have very little variation (less than 100 m). All the other profiles (a,b,d,e and h) exhibit intermediate variation in topography. In most cases, the slope is less than 2 degrees, with profiles, c, h and i exhibiting the steepest slopes (Table 4.1).

B) The profiles were further analyzed to identify sudden changes in topography. These changes were attributed to geological features such as faults, or to topographic artefacts (appearing as topographic 'holes') in the dataset (Herrick 2012). An example of a meaningless topographic artefact is shown by the dotted line in profile f. In selecting the profiles, these artefacts are avoided where possible by examining the topography layer in JMARS. In all other cases, topographic variation is meaningful. For example, in profile b, there is a sharp down-drop of 200 m at the 30 km mark, that coincides with the southeastward extrapolated extent of a lava flooded valley, suggesting a fault.

C) Two profiles (g and i) that are taken perpendicular to dominant lineament sets are used to estimate layer spacing. Profile g shows a relatively low variation in topography across a set of lineaments. Over the distance of 65 km, there are approximately 13 lineaments present. On average that would allow for lineament spacing of 5 km, based on the assumption that these lineaments represent vertical layers. On the other hand, if these lineaments represent subhorizontal layers, the spacing between them would be almost negligible. Profile i shows a high variation in topography (greater than 100 m). Over the distance of 50

km, there are approximately 8 lineaments present. That would allow for lineament spacing of 7 km, assuming these lineaments represent vertical layers. If they were horizontal layers, the lineament spacing would be 0.2 km.

4.2 Calculating Dip of Planar Surfaces

4.2.1 Dip

Strike and dip measurements are simple yet important calculations for structural and stratigraphic analysis in geological sciences. The dip of a planar geological feature is defined as the amount this layer is tilted from the horizontal. The strike value is the compass direction along the horizontal line of a planar geological feature. Generally, these measurements are done in the field directly at the outcrop of a geological feature. In planetary sciences, this approach is not possible for obvious reasons. Therefore, the only way to get information about the spatial orientation of planar geologic features on Venus is through the use of remote sensing data. This study uses JMARS to obtain the horizontal position (x and y axis coordinates, quoted as “North” and “East” in equation 1) and its elevation (z coordinate, quoted as “Elevation” in equation 1) along individual lineaments and uses XLSTAT for mathematical calculations of the orientation of the best fit associated planar feature.

4.2.2 Methodology for PCA (Principal Component Analysis)

Principal component analysis (PCA) is a widely used technique for reducing the dimensionality of data sets (Kirschvink, 1980; Jolliffe and Cadima, 2016; Lever et al., 2017; Hopkins and John, 2018; Frank and Smith, 2019;). PCA is a linear transformation of the

orthogonal coordinate axes to a new reference frame (new coordinate axes) that corresponds to the inherent geometry of the data set via least squares fit. Each axis in the new system is associated with a measure of its variance. Two of the axes are positioned to represent the maximum and minimum direction of variance (F1, F3), while the other is intermediate (F2). PCA yields eigenvectors (F1, F2 and F3) (Figure 4.6) which indicate the direction of the new axes. Eigenvalues (λ_{F1} , λ_{F2} , λ_{F3}) associated with each eigenvector represent variance (σ^2) of data along the new axes. In this study, F1 and F2 are in the plane of the layer; F3 is perpendicular to the plane (Figure 4.6) and is used to calculate dip using equation (1). PCA was calculated using XLSTAT (Chapter 2).

$$(1) \quad DIP = \arctan \left(\frac{\sqrt{North^2 + East^2}}{Elevation} \right)$$

Where North, East and Elevation are components of the F3 eigenvector.

Figure 4.6: eigenvectors associated with plane; F1 and F2 are in the plane of the layer and F3 is perpendicular.

The uncertainty in the best fit plane is based on Kirschvink (1980) and was originally designed for the analysis of paleomagnetic demagnetization data. The uncertainty in such a best-fit plane was determined from the variance. For the best fit plane (and line) Kirschvink (1980) considered a rectangular box with dimensions based on the variance $\sigma_{\max}$, σ_{int} , $\sigma_{\min}$, and determined the maximum angular uncertainty (which he termed the Maximum Angular Deviation (MAD)) as given by equations 2 and 3 for MAD plane and MAD line, respectively.

$$(2) \quad \text{MAD}_{\text{plane}} = \arctan \left(\sqrt{\frac{\lambda_{F3}}{\lambda_{F2}} + \frac{\lambda_{F3}}{\lambda_{F1}}} \right)$$

$$(3) \quad \text{MAD}_{\text{line}} = \arctan \left(\sqrt{\frac{\lambda_{\text{int}} + \lambda_{\text{min}}}{\lambda_{\text{max}}}} \right)$$

4.2.3 Methodology for Calculating Dip

a

b

North (m)	East (m)	Elevation (m)
9390	16191	864
22192	22870	1085
30429	24428	1148
34994	25096	1039
42675	26989	1167
48241	27434	1357
54363	27434	1218

c

EIGENVALUES

	F1	F2	F3
Eigenvalue	2.785	0.155	0.060

d

EIGENVECTORS

	F1	F2	F3
North (m)	0.580	-0.502	-0.642
East (m)	0.585	-0.292	0.757
Elevation	0.567	0.814	-0.125

e

CALCULATING DIP

$$DIP = TAN^{-1} \left(\frac{\sqrt{-0.642^2 + 0.757^2}}{-0.125} \right)$$

$$Dip = 83^{\circ}$$

f

MAXIMUM ANGULAR DEVIATION

$$MAD = \arctan \left(\sqrt{\frac{0.06}{0.155} + \frac{0.06}{2.785}} \right)$$

$$MAD = 33^{\circ}$$

Figure 4.7: Example of calculation of best fit dip and uncertainty from lineament data. a: example of lineament (red line) chosen on Salus Tessera. b: xyz points along associated lineament (red line). c: eigenvalues calculated using PCA. d: eigenvectors calculated using PCA. e: calculated dip using equation 1. f: maximum angular deviation (MAD) calculated using equation 2.

The following steps are required to estimate dip of planes associated with observed lineaments on Salus Tessera: A) Identify lineaments which exhibit a change of elevation along the lineament (Figure 4.7a). B) Take measurements along the chosen lineament recording both horizontal position and elevation (Figure 4.7b). A minimum lineament length of 20 km is suggested due to the 10-20 km horizontal footprint for the elevation measurement. A minimum elevation change of 200 m is suggested due to the 50-100 m vertical uncertainty. Areas with topographic artefacts are avoided and chosen lineaments are assumed to represent the surface trace of planar features. C) The data points for each lineament are input into Microsoft Excel. The dip and MAD are then calculated using equations 1 and 2, respectively. Lastly, the calculated dip of the inferred planar feature is used to constrain the interpretation of the lineament set.

4.3 Results

4.3.1 Calculated examples for Salus Tessera

	LINEAMENT	DIP (°)	MAD (°)
A		86	4
B		83	33
C		87	13
D		65	18
E		82	25
F		46	14
G		85	5

Figure 4.8: Lineament sets chosen for analysis on Salus Tessera (top) and their associated dip and MAD values (bottom). The dip direction for each lineament is towards the concave side.

The dip and MAD are calculated using PCA for 7 profiles (Figure 4.8). Calculations for each lineament can be found in Appendix A. Of those lineaments, 5 (profiles A-C, E and G) appear to be associated with subvertical planes and 2 (profiles D and F) are associated with planes of intermediate dip (Figure 4.9).

PROFILE D:

LINEAMENT	DIP (°)	MAD (°)
	46	14

PROFILE F:

LINEAMENT	DIP (°)	MAD (°)
	65	18

Figure 4.9: Close-up look at two lineaments that are associated with intermediate dips

4.3.2 Uncertainties Associated with PCA Calculations

Given a vertical uncertainty of 50-100 m in Venusian topographic data, all topographic variations that exceed that value can be considered 'real', except in the vicinity of topographic artefacts in the dataset. On the other hand, because there is a horizontal 'footprint' of 10-20 km, there is uncertainty in which specific feature in the Magellan image (75-100 m per pixel resolution) can be linked with a topographic change. The topographic value is essentially averaging over that footprint size. As a result, the topographic data may be smoothed over these areas and the true topographic variation is likely to be more extreme. These large uncertainties in the topographic data imply larger uncertainties in the dips calculated from PCA. This technique would be better applied in areas of the higher resolution topographic data created by Herrick (2012), which are not available for Salus Tessera.

4.3.3 Role of erosion

If the lineaments are only a result of tectonic features (extensional fractures, grabens, strike slip faults) then differential erosion is not required, which is the implicit assumption of most previous studies. However, the possibility of erosion in tesserae (Chapter 3) allows additional interpretations for lineaments. This is especially true for intermediate to shallow dipping planar features (as calculated using the methodology above) which can be sills, volcanic or sedimentary units exposed by differential erosion.

4.4 Conclusion

Tesserae are known to exhibit a variety of lineaments that can be linear or curved, and closely or widely spaced. It can be assumed that these represent the surface trace of planar

geological features. Purely tectonic interpretations of associated planar features include faults, grabens and fold crests. However, given the possibility of tesserae erosion, then additional types of interpretations are possible, such as layered geological units (sedimentary or volcanic) exposed by differential erosion. A key parameter in interpreting the nature of these planar units is to assess their dip. A methodology is developed using PCA to calculate dips and their uncertainties and applied to 7 lineaments in Salus tessera.

5. Chapter: Summary and Conclusions

5.1 Summary

Tesserae are highly deformed terrains and are generally located within crustal plateaus on Venus. Tesserae encompass 8% of the Venusian surface and are dominantly located within equatorial and northern latitudes. They are characterized by high radar backscatter and complex deformation patterns including multiple sets of intersecting lineaments. The processes by which tesserae are formed have not been well understood and multiple models have been put forth in attempts to explain their origin and formation.

An impediment to their full understanding is the unquestioned implicit assumption in the literature that tesserae did not experience erosion. An absence of erosion is clear for the stratigraphically younger basaltic plains and edifice magmatism and is consistent with the current atmospheric temperatures of 450°C. A recently published climate model allows for the presence of liquid water on ancient Venus, therefore opening up the possibility of identifying erosional features in the stratigraphically oldest units called tesserae.

5.2 Fluvial Erosion of Tesserae

Chapter 3 considered the geomorphology of tesserae and explicitly considered the role of fluvial erosion. However, the analytical uncertainty in elevation values (50-100 m vertical and horizontal footprint of 10-20 km) prevents easy identification of valleys in tesserae. Therefore, a proxy approach was developed and used to locate low areas ('valleys') in tesserae. Younger basaltic plains lavas overlap the margins of tesserae and fill any pre-existing valleys. Partial flooding by lava flows of the margins in tesserae represents a datum

that distinguishes valleys from bordering topographic highs (peaks and ridges). These valley patterns were then compared against terrestrial stream systems. A total of 8 examples of valley patterns in tesserae regions were compared with stream drainage patterns on Earth. It was evident that these patterns were morphologically similar to 5 of the 6 recognized stream valley pattern types on Earth. In these cases, the inference was that the valleys were originally formed by stream erosion and these same valleys were infilled by later lava flows. In addition, one area shows a tear drop shaped 'island', consistent with the local inferred direction of stream flow.

The role of wind and glacial erosion were also considered. Yardangs (wind erosion features) can be seen on both Earth and Venus. However, they are characterized with parallel and elongated ridges which could represent only some of the observed valley patterns types. Similarly, essential features of glacial erosion (U-shaped valleys, cirques, hanging valleys etc...) were also not identified on tesserae due to insufficient topographic resolution. As a result, the role of glacial erosion cannot be assessed with the available data.

The recognition of fluvial patterns (Chapter 3) in tesserae is a paradigm shift and has significant implications. One of the implications is developed in Chapter 4 (summarized below in section 5.3) and others are mentioned in the Future Work section (section 5.4).

5.3 Interpretation of Lineament Sets in Tesserae

Chapter 4 considers the origin of the multiple sets of intersecting lineaments that characterize tesserae. The previous interpretation of tesserae lineaments was based on the implicit assumption that tesserae did not exhibit erosion. In the absence of erosion, lineaments could only represent the surface expression of features such as fold crests, faults

and grabens. In Chapter 4, tesserae lineaments were assessed from the viewpoint that erosion could have occurred. This allowed additional types of lineament interpretations, namely as the surface trace (exposed by erosion) of the edges of a set of sills, volcanic flows or sedimentary formations. To distinguish between these different interpretations requires insight into the dip of planar features associated with lineament sets. Steeply dipping features could represent faults and grabens while shallowly dipping features could represent sills, volcanics and sedimentary formations. Features of intermediate dips could represent listric faults, tectonically tilted sequences of sills, volcanics and sedimentary formations. Chapter 4 develops a methodology for determining the dip of planar surfaces from surface lineaments.

Principal Component Analysis (PCA) was applied to traces of curved lineaments which varied in elevation. For each analysis, a series of xyz coordinates were obtained (x and y from the Magellan SAR images and z from the topographic data) and the dip for its associated plane was then calculated. Furthermore, an equation used to calculate Maximum Angular Deviation (MAD), a measure of uncertainty, was adapted from the paleomagnetic literature. PCA/MAD analysis was applied to 7 lineament traces from various regions of a small tesserae called Salus Tessera. It was found that majority of the curving lineaments represented sub-vertical planar features, although two have intermediate dips of 46 and 65 degrees.

5.4 Recommendations for Future Work

The recognition of erosion in tesserae (Chapter 3) is a paradigm shift and has numerous implications. As discussed above (Chapter 4 and section 5.3) this allows for the potential recognition of volcanic flows, sedimentary formations or intrusive sills through differential

erosion that exposes the stratigraphy as lineament sets. Additional implications discussed below represent important avenues of future research that will build on the results of this thesis.

As discussed in other Chapters, many researchers have attempted to map geological domains within tesserae and to develop a geological history, typically implicitly assuming no erosion has occurred. In the absence of erosion, all the structures and features observed at the surface must represent primary features that were always at the surface since they were formed. However, if tesserae did experience erosion, then it is possible that different domains may represent rocks uplifted and eroded from different crustal depths. The new erosion paradigm introduced in this thesis therefore allows a much richer array of geological and tectonic interpretations of tesserae that was possible when no erosion was considered.

In this thesis, 8 regions of partially flooded tesserae were mapped and compared with terrestrial stream patterns. As noted in Chapter 3 the type of inferred stream valley pattern is reflective of the type of geology and tectonics. A key step going forward is expanding the mapping of stream valley patterns to tesserae from all regions of Venus, in order to provide reconnaissance-level understanding of global tesserae geology and tectonics.

As a result of erosion, tesserae would record a much greater period of Venusian history than presently thought. The age of Venusian features is determined by impacting crater counting and the age of tesserae is comparable to the age of the younger plains flows. However, if tesserae have experienced erosion then meteorite impact craters would only start being preserved when the global warming event occurred and the water cycle was shut off. Therefore, tesserae may preserve a much longer history, potentially billions of years

prior to the global warming event at ~700 Ma. Future mapping and analysis can therefore try to characterize this longer geological history preserved in tesserae.

Appendix A: Calculations for dip, maximum angular deviation and strike for lineaments on Salus Tessera. See Figure 4.8 for location of analyzed lineaments. The methodology is explained in section 4.3.

Lineament 1:

North	East	Elevation	North (m)	East (m)	Elevation	North (m)	East (m)	Elevation
-4.131	48.764	1354.5	-459862.92	5428408.48	1354.5	70137	28408	1355
-4.172	48.762	1327	-464427.04	5428185.84	1327	65573	28186	1327
-4.203	48.752	1417	-467877.96	5427072.64	1417	62122	27073	1417
-4.248	48.74	1417	-472887.36	5425736.8	1417	57113	25737	1417
-4.291	48.738	1606.5	-477674.12	5425514.16	1606.5	52326	25514	1607
-4.322	48.73	1606.5	-481125.04	5424623.6	1606.5	48875	24624	1607
-4.393	48.711	1628	-489028.76	5422508.52	1628	40971	22509	1628
-4.504	48.688	1535.5	-501385.28	5419948.16	1535.5	28615	19948	1536
-4.609	48.662	1439	-513073.88	5417053.84	1439	16926	17054	1439
-4.66	48.633	1295.5	-518751.2	5413825.56	1295.5	11249	13826	1296
-4.727	48.615	1369.5	-526209.64	5411821.8	1369.5	3790	11822	1370

Eigenvalues:

	F1	F2	F3
Eigenvalue	2.033	0.964	0.004

Eigenvectors:

	F1	F2	F3
North (m)	0.689	-0.186	-0.701
East (m)	0.698	-0.090	0.710
Elevation	0.195	0.978	-0.067

CALCULATING DIP		CALCULATING UNCERTAINTY		CALCULATING STRIKE
0.9977		0.061		-1.014035629
-14.797		1.730967495		-0.792366959
-1.503317034		0.03538469		-45.39928256
-86.1337		0.035369933		SOUTH EAST
		2.026547906		
				44.60071744

Lineament 2:

North	East	Elevation	North (m)	East (m)	Elevation	North (m)	East (m)	Elevation (m)
0.803	45.061	863.5	89389.96	5016190.52	863.5	9390	16191	864
0.918	45.121	1084.5	102191.76	5022869.72	1084.5	22192	22870	1085
0.992	45.135	1148	110429.44	5024428.2	1148	30429	24428	1148
1.033	45.141	1039	114993.56	5025096.12	1039	34994	25096	1039
1.102	45.158	1166.5	122674.64	5026988.56	1166.5	42675	26989	1167
1.152	45.162	1356.5	128240.64	5027433.84	1356.5	48241	27434	1357
1.207	45.162	1218	134363.24	5027433.84	1218	54363	27434	1218

Eigenvalues:			
	F1	F2	F3
Eigenvalue	2.785	0.155	0.060

Eigenvectors:			
	F1	F2	F3
North (m)	0.580	-0.502	-0.642
East (m)	0.585	-0.292	0.757
Elevation	0.567	0.814	-0.125

CALCULATING DIP		CALCULATING UNCERTAINTY		CALCULATING STRIKE
0.9922		0.246		-1.179832493
-7.968		1.714503195		-0.867710072
-1.445943833		0.143437683		-49.71612496
-82.8465		0.142465938		SOUTH EAST
		8.162696944		
				40.28387504

Lineament 3:

North	East	Elevation		North (m)	East (m)	Elevation		North (m)	East (m)	Elevation
-1.385	48.396	1394		-154178.2	5387442.72	1394		45822	387443	1394
-1.373	48.375	1582.5		-152842.36	5385105	1582.5		47158	385105	1583
-1.363	48.344	1838		-151729.16	5381654.08	1838		48271	381654	1838
-1.332	48.275	2067.5		-148278.24	5373973	2067.5		51722	373973	2068
-1.283	48.189	2081		-142823.56	5364399.48	2081		57176	364399	2081
-1.242	48.127	1845		-138259.44	5357497.64	1845		61741	357498	1845
-1.201	48.076	1779		-133695.32	5351820.32	1779		66305	351820	1779
-1.148	48.018	1535.5		-127795.36	5345363.76	1535.5		72205	345364	1536
-1.115	47.797	1580		-124121.8	5320762.04	1580		75878	320762	1580
-1.084	47.947	1547.5		-120670.88	5337460.04	1547.5		79329	337460	1548

Eigenvalues:			
	F1	F2	F3
Eigenvalue	2.043	0.924	0.033

Eigenvectors:			
	F1	F2	F3
North (m)	0.686	0.151	0.711
East (m)	-0.678	-0.222	0.701
Elevation	-0.264	0.963	0.050

CALCULATING DIP		CALCULATING UNCERTAINTY		CALCULATING STRIKE
0.9988		0.181		0.985353099
19.999		1.722586374		0.778020818
1.520835886		0.104970561		44.57730926
87.1375		0.104587539		NORTH EAST
		5.992424585		
				-45.42269074

Lineament 4:

North	East	Elevation	North (m)	East (m)	Elevation	North (m)	East (m)	Elevation
0.1484	48.5	880	16519.888	5399020	880	520	399020	880
0.165	48.4736	810.5	18367.8	5396081.152	810.5	2368	396081	811
0.1729	48.4473	810.5	19247.228	5393153.436	810.5	3247	393153	811
0.1777	48.3789	831	19781.564	5385539.148	831	3782	385539	831
0.1777	48.374	1118	19781.564	5384993.68	1118	3782	384994	1118
0.1777	48.3437	1221.5	19781.564	5381620.684	1221.5	3782	381621	1222
0.1777	48.3154	1221.5	19781.564	5378470.328	1221.5	3782	378470	1222

Eigenvalues:

	F1	F2	F3
Eigenvalue	2.429	0.524	0.048

Eigenvectors:

	F1	F2	F3
North (m)	-0.554	-0.683	0.476
East (m)	0.632	0.027	0.774
Elevation	-0.542	0.729	0.417

CALCULATING DIP		CALCULATING UNCERTAINTY		CALCULATING STRIKE
0.9087		0.218		1.627654207
2.177		1.718229292		1.019869534
1.140191777		0.127093661		58.43421996
65.3282		0.126415911		NORTH EAST
		7.243098163		
				-31.56578004

Lineament 5:

North	East	Elevation	North (m)	East (m)	Elevation	North (m)	East (m)	Elevation
0.7148	47.6475	806.5	79571.536	5304119.7	806.5	19572	304120	807
0.7002	47.6719	828.5	77946.264	5306835.908	828.5	17946	306836	829
0.6816	47.6934	712	75875.712	5309229.288	712	15876	309229	712
0.6631	47.7158	712	73816.292	5311722.856	712	13816	311723	712
0.6406	47.7314	655	71311.592	5313459.448	655	11312	313459	655
0.6182	47.7451	615.5	68818.024	5314984.532	615.5	8818	314985	616

Eigenvalues:

	F1	F2	F3
Eigenvalue	2.917	0.069	0.014

Eigenvectors:

	F1	F2	F3
North (m)	-0.581	-0.281	0.763
East (m)	0.578	0.517	0.631
Elevation	-0.572	0.808	-0.138

CALCULATING DIP		CALCULATING UNCERTAINTY		CALCULATING STRIKE
0.9904		0.119		0.826449631
-7.176		1.727931216		0.690661986
-1.432340707		0.06909356		39.57201685
-82.0671		0.068983924		NORTH EAST
		3.952487724		-50.42798315

Lineament 6:

North	East	Elevation	North (m)	East (m)	Elevation	North (m)	East (m)	Elevation
-0.4951	48.0518	475	-55114.532	5349126.376	475	885	349126	475
-0.4736	48.0596	475	-52721.152	5349994.672	475	3279	349995	475
-0.4434	48.0674	502	-49359.288	5350862.968	502	6641	350863	502
-0.4004	48.0693	617	-44572.528	5351074.476	617	11427	351074	617
-0.376	48.0684	617	-41856.32	5350974.288	617	14144	350974	617
-0.3535	48.0659	751.5	-39351.62	5350695.988	751.5	16648	350696	752
-0.3193	48.0566	741.5	-35544.476	5349660.712	741.5	20456	349661	742

Eigenvalues:

	F1	F2	F3
Eigenvalue	2.100	0.863	0.038

Eigenvectors:

	F1	F2	F3
North (m)	0.673	-0.186	-0.716
East (m)	0.338	0.938	0.074
Elevation	0.658	-0.292	0.694

CALCULATING DIP		CALCULATING UNCERTAINTY		CALCULATING STRIKE
0.7196		0.194		-0.103069111
1.036		1.72115613		-0.102706444
0.803252349		0.112693334		-5.884645744
46.0230		0.112219876		SOUTH EAST
		6.429725271		
				84.11535426

Lineament 7:

North	East	Elevation	North (m)	East (m)	Elevation	North (m)	East (m)	Elevation
-2.1689	47.7227	1183.5	-241441.948	5312490.964	1183.5	8558	312491	1184
-2.1514	47.6992	1184.5	-239493.848	5309874.944	1184.5	10506	309875	1185
-2.1357	47.6797	1184.5	-237746.124	5307704.204	1184.5	12254	307704	1185
-2.1094	47.665	1229	-234818.408	5306067.8	1229	15182	306068	1229
-2.0801	47.6445	1303	-231556.732	5303785.74	1303	18443	303786	1303
-2.0557	47.6201	1214.5	-228840.524	5301069.532	1214.5	21159	301070	1215
-2.043	47.5957	1214.5	-227426.76	5298353.324	1214.5	22573	298353	1215
-2.0303	47.5762	1171	-226012.996	5296182.584	1171	23987	296183	1171

Eigenvalues:

	F1	F2	F3
Eigenvalue	2.042	0.953	0.005

Eigenvectors:

	F1	F2	F3
North (m)	0.696	-0.098	0.712
East (m)	-0.684	0.213	0.698
Elevation	0.221	0.972	-0.081

CALCULATING DIP		CALCULATING UNCERTAINTY		CALCULATING STRIKE
0.9967		0.068		0.980886803
-12.275		1.730729925		0.775749654
-1.489509021		0.039076461		44.44718116
-85.3426		0.039056589		NORTH EAST
		2.23777773		
				-45.55281884

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