# ABSTRACT

Gravitational Indications of Subduction on Venus

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While Venus lacks global plate tectonics, there has been evidence of localized subduction on Venus. The goal of this study is to observe and forward model the gravity gradients of a subducted slabs on Earth and Venus. Our modeled results are consistent with subduction in at least three locations on Venus: Artemis Corona, Quetzalpetlatl Corona, and Astkhik Plateau. We also have identified a trend at terrestrial and Venusian subduction zones of a higher geothermal gradient on the overriding plate side of the trench and a lower geothermal gradient on the outboard side. The modeled subducting slabs on Earth and Venus are found to be negatively buoyant. However, the Venus slabs tended to be slightly less negatively buoyant. We hope that these methods will be repeated for smaller corona once VERITAS’s gravity data has been recovered.

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# CHAPTER 1

## Introduction

In many regards, Venus is the most Earth-like extraterrestrial planet that we have found. Venus and Earth have a similar mass, bulk composition, and distance from the Sun, indicating that the two planets formed under similar starting conditions. Based on these similarities, we might expect Venus to be a planet much like Earth is today, with vast amounts of liquid water and environmental conditions suitable for life. Instead, we find Venus to be a harsh planet with a surface temperature of ~475°C and a thick 92 bar atmosphere largely consisting of CO2 that produces an extreme greenhouse effect. Differences between Venus and Earth extend below the surface as well: the tectonic regime on Venus is different from Earth’s, and Venus has no core-generated magnetic field. The planets’ stark differences can teach us much about their respective evolutionary paths and can help us to understand the diversity of Earth-like exoplanets.

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Figure : Surface of Venus as seen by a Venera 13. (Image processed by Don Mitchell).

The surface of Venus was first observed by the mission Venera 8, followed by a series of Venera missions that landed on the surface and sampled rocks on the surface that were determined to be basaltic in composition. Basaltic crustal rocks likely imply that Venus’s mantle, like the Earth’s, is composed of peridotite (Fegley, 2004). Surface basalts have several geochemical similarities to mid-ocean ridge basalts, including approximately 8 wt% FeO; since FeO partitions similarly into partial melts and the melt residuum, this implies that Venus’s mantle has an iron content similar to Earth’s (Treiman, 2007). The planet has a bulk density of 5243 kg/m3, which suggests that Venus’s core is only slightly smaller than Earth’s core (Margot et al., 2021). Cloud-penetrating radar instruments (Magellan spacecraft) and lander probes (Venera 15 and 16) were able to image the surface, identifying widespread volcanic deposits and volcanic structures (Barsukov et al., 1986; Saunders et al., 1990) (Figure 1).

Most of the surface features on Venus can be classified into three different categories: low-lying volcanic plains, volcanic rises, or crustal highlands. The majority of the planet’s surface consists of the volcanic plains. The volcanic rises have been shown to be partially supported by dynamic flow in the mantle (James et al., 2013; Smrekar et al., 2010). The origin and mechanisms by which the crustal highlands formed remain controversial. Both upwellings and downwellings are the primary proposed mechanism for explaining their formation. The upwelling scenario describes the crustal highlands being formed through crustal thickening due to a large volume of partial melt above a mantle plume. The uplift during this formation mechanism would explain the stratigraphically ribbon-like tectonic features observed at the highlands (Phillips & Hansen, 1998). Complex ridge terrain has also been found which is comparable to compressional tectonic features on Earth. This could be consistent with the theory that the highland terrain was formed through mantle downwelling (Bindschadler et al., 1992). While it is surprising how vastly the planets Earth and Venus differ from one another, this gives us the opportunity to use each planet as a laboratory for the other. One explanation for the planets’ differences is that they diverged on distinct evolutionary paths for some reason. Alternatively, Venus and Earth are evolving at different rates, and Venus offers a peek into Earth’s past or future. Either way, there is much to be learned about Earth from studying Venus.

This study seeks to explore the use of our current gravity data to test the hypothesis of small-scale subduction on Venus. Subduction is here defined to be the phenomenon in which one lithospheric plate (the “outboard” or “downgoing” plate) moves under an adjacent plate (the “overriding” plate) and sinks some distance into the sub-lithospheric mantle. In addition to testing the hypothesis of subduction, this study yields best-fit parameters for the subduction geometry and thermal state. Finally, the techniques introduced here will lay the groundwork for future investigations with improved data—from upcoming robotic missions—to study smaller-scale structures in greater detail.

# CHAPTER 2

## Describing and Identifying Subduction on Venus

### 2.1 Tectonic Regimes

The presence and extent of subduction is largely controlled by a planet’s tectonic regime, and initiation of subduction can play a key role in the transitions between different tectonic regimes. There are a variety of tectonic regimes that have been attached to planets or satellites in our solar system: mobile lid, stagnant lid, heat-pipe regime, episodic, and plutonic-squishy lid. A mobile lid tectonic regime, like its name implies, is characterized by high amount of surface motion. Earth is in a variation of a mobile lid tectonic regime that has high surface heat flow, tectonic plate boundaries, and subduction. In contrast, a stagnant lid is characterized by a lack of lateral motion of the surface; planets in this regime are sometimes described as a “one-plate” planets. Mars, Mercury, and the Moon are widely considered to have stagnant lids, and the term used by some to describe the more geologically active Venus (Ghail, 2015; Stern et al., 2018). The heat-pipe regime is a common explanation for the high volcanic activity and tidal heating of Jupiter’s moon Io. In this regime, internal heat is lost through volcanic conduits that carve through the lithosphere to transport material to the planet’s surface (Moore & Webb, 2013).

The various tectonic regimes described above yield testable predictions for planetary heat flux, crustal thickness, and surface age. Assuming a near steady state balance between radioactive heat production and surface heat loss, the mean surface heat flow for Venus in these regimes would be ~63 mW/m2(D. L. Turcotte, 1995). Using this estimated heat flow and a thermal conductivity of 3 W/mK, the mean thermal gradient would be 21 K/km. However, based on impact modeling, Bjonnes et al., (2021) found that 28 mW/m2 is an upper bound on for heat flow on Venus leading to an upper bound on geothermal gradients of ~10 K/km. These regimes would also tend to create a very thick crust; however, observations show that Venus has a thin crust around ~10-40 km (James et al., 2013). For these reasons, neither mobile lid nor stagnant lid can describe Venus’s entire tectonic history. An episodic regime is a hybrid of the mobile lid and stagnant lid regimes, in which a stagnant lid is punctuated by periods of high mobility that are associated with global resurfacing. Within this regime, the resurfacing event could occur in a short time, or ‘catastrophically’, followed by a period of dormancy or calm while internal heat builds until the next resurfacing event occurs. Episodic regimes yield relatively high heat flux during the high-mobility pulses and relatively low heat flux during quiescent periods, so this could explain lower-than-expected heat flux over Venus’s recent geologic history. Models have predicted ~5-8 global lithospheric resurfacing events in Venus’s history (Armann & Tackley, 2012). An observation of the nearly random distribution of craters on the surface—and the relative lack thereof—is consistent with the theory that the surface was uniformly resurfaced ~300-700 Ma (Herrick & Parmentier, 1994). However, the distribution of craters could also be explained by patchwork “equilibrium” resurfacing (Hauck et al., 1998). A gradual decline in the rate of equilibrium resurfacing could explain Venus’s heat loss budget and its lower current heat flow.

There has been a new tectonic regime proposed recently called plutonic-squishy lid that includes more intrusive volcanism. This regime is specifically characterized by a set of small plates that are separated by regions weakened by plutonism. This regime requires high intrusive efficiency, high mantle temperatures, and a phase change from basalt to eclogite. This causes delamination of the lithosphere to occur close to the weakened areas (Figure 2) (Lourenço et al., 2020). Lourenço et al., (2018) demonstrated that intrusive magmatism can cool the mantle more effectively than extrusive magmatism and allows for an exceedingly high surface heat flux. This is thought to be the case for the Archean Earth (Lenardic, 2006); if a plutonic squishy lid were in place on Earth at this time, this could have implications for subduction initiation on Earth.

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Figure : Evolution of a plutonic-squishy lid (Lourenço et al., 2020)

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Figure : Surface mobility modeled through time, showing a transitional period between a mobile-lid and stagnant-lid regime. (Weller & Kiefer, 2020)

While it may be easy to assign a single tectonic regime to a planet, it may be more appropriate to assign them to a planet’s current evolutionary stage. It is possible that a planet might transition from one tectonic regime to another. It is possible that Earth may have looked like Venus and been in a plutonic-squishy lid regime before it turned into a mobile plate regime. It has also been suggested that Venus is currently transitioning from a mobile lid to a stagnant lid, showing a planet that is in-between-regimes. This transition was proposed to be due to an increasing yield stress as the planet experiences water loss and an increase in surface temperature (Weller & Kiefer, 2020). This theory of a gradual regime change avoids any catastrophic event but instead, during the transition period, we can find both a mobile lid and stagnant lid reflected at different parts of the planet (Figure 3).

### 2.2 Initiation of Plate Tectonics

For any planet, the initiation mechanism and time of plate tectonics and subduction initiation are a mystery and widely argued. Plate tectonics and large-scale subduction are currently only found on Earth. Whether plate tectonics formed from subduction initiation or by another mechanism, a proposed mechanism must explain the cause of subduction initiation when a lithosphere or thermal boundary layer deforms and sinks into the deep mantle. The subduction initiation mechanism must first overcome the temperature-dependent viscosity through brittle deformation and breaks the lithosphere. The lower density crust and depleted mantle of the lithosphere also needs to become gravitationally unstable to begin sinking into the denser asthenosphere mantle. This instability could arise chemically from a transition from basalt to eclogite or through thermal contraction of a cooled lithosphere (Korenaga, 2013).

Stern & Gerya (2018) reviews the more prevalent proposed subduction initiation mechanisms and organizes them into three categories: compression, extension, and spontaneous initiation. Compression induced subduction includes plate motion causing the growth of compressional stress in a plate until rupture occurs withing the plate (Agard et al., 2007), shear-heating induced lithospheric-scale fracture zones causing local subduction (Thielmann & Kaus, 2012), and compression-induced conversion of faults or fracture zones into subduction trenches (Maffione et al., 2017). An extension caused initiation mechanism could be from the tensile decoupling of the continental and oceanic lithospheres due to rifting (Kemp & Stevenson, 1996). There are spontaneous subduction initiation mechanisms, which are not associated with compression or extensional stresses, such as the loading of the lithosphere at continental or arc margins (Regenauer-Lieb et al., 2001). Also, a passive margin, transform fault, or fracture could collapse due to a lateral thermal buoyancy asymmetry between the two sides of the lithosphere (Dymkova & Gerya, 2013; Rey et al., 2014). Tectono-magmatic plume-lithosphere interactions, small scale convection in the upper asthenosphere, and large asteroid impact events have been also proposed as subduction initiation mechanisms (Gerya, 2014; Hansen, 2007; Solomatov, 2004). The edges of mantle plumes have been shown to be favorable settings for subduction to begin (Whattam & Stern, 2015). Laboratory experiments of plume induced subduction shows that when plumes for fractures in the lithosphere, it can lead to bending and subduction of the lithosphere (Davaille et al., 2017a). With the current absence of plate tectonics on Venus and the large amount of evidence for plume activity, plume-induced subduction seems the most likely initiation mechanism if subduction has occurred on Venus.

### 2.3 Tectonics on Venus

Venus is not tectonically active in the same way as Earth, but it is not believed to be inactive. The planet has evidence of a unique tectonic history that may differ from an active terrestrial tectonic framework. One example of this is that the highly deformed “tesserae” (plural of “tessera”), which moderately covers the crustal plateaus and is characterized by high radar backscatter (indicating roughness from centimeter to meter scale) and an elevated terrain (Figure 4). The tesserae cover ~8% of the surface of the planet and are morphologically distinct from the volcanic plains that prevail over the rest of the planet. The tesserae are stratigraphically the oldest material on the planet (Ivanov & Head, 1996), making them and the highlands on which they are found important subjects of study to understand the geological history of the planet. Their formation has been attributed to both the mantle upwellings and downwellings that created the crustal plateaus. Tellus Regio specifically shows signs of smaller tesserae that formed regionally and collected into the single plateau that we find today (Gilmore & Head, 2018). Near-infrared emissivity observations at Alpha Regio found that the emissivity is lower at the tesserae than the surrounding plains. Possible reasons for this are that the tesserae could be more mafic and covered in a low emissivity weathering product, or they could be mafic and have different grain size than the volcanic plains, or they could be more felsic in composition (Gilmore et al., 2015; Resor et al., 2021). If a granitic tessera exists, it would be a record of an extinct plate tectonic regime on a water-rich planet (Way et al., 2016; Way & del Genio, 2020). In that case Venus may be a peak into the evolutionary path of an Earth-like planet that has terrestrial and exoplanet implications.



Figure : Tessera terrain in Ovda Regio on Venus (a radar image obtained with Magellan spacecraft). This image is centered at 1°N, 81°E.

Another example of tectonic activity are the “coronae” (plural of “corona”), which are quasi-circular tectonic fracture features unique to Venus that are associated with volcanic activity (Figure 5). There are an abundant number of these surface features (>500), ranging in size from 60 km to over 2000 km across (Stofan et al., 1991). Coronae are not randomly distributed on Venus like impact craters, and they are mainly found near chasmata or fracture belts (O’Rourke & Smrekar, 2018; Stofan et al., 1992). These features are generally thought to be formed from the relaxation of small-scale mantle upwellings (Gerya, 2014; Stofan et al., 1991). The mantle upwelling weakens the lithosphere, resulting in lithospheric dripping, subduction, embedded plume, or plume underplating. Different coronae show different types of lithosphere-plume interaction and levels of activity. At least 37 of the large coronae have been identified as active, giving evidence of continuing plume activity (Gülcher et al., 2020).

Whichever tectonic regime Venus may be in, it does not seem as simple as a continuous lithosphere. The surface has been extensively deformed. Byrne et al., (2021) reports the existence of globally distributed crustal blocks that move relative to one another in the Venusian lowlands, although the amplitude of lateral translation is small relative to plate motion on Earth. It is also seen that some of this surface motion has occurred more recently than the emplacement of the volcanic plain material. These findings seem to point towards a plutonic-squishy lid regime on Venus and places the planet in a different category than the single plate planet regime, and static continuous lithosphere that we see on Mercury, Mars, and the Moon.

### 2.4 Venus Subduction

Plate tectonics and subduction on Earth performs the role of recycling the planet's crust and releasing internal heat. Without global plate tectonics, Venus does not experience significant crustal recycling and the planet's heat loss likely occurs through volcanism and mantle plume activity (Gerya, 2014). Despite the lack of plate tectonics, localized subduction on Venus has been hypothesized. It has been suggested that mantle plume activity is most likely responsible for subduction initiation on Venus (Davaille et al., 2017b; Gülcher et al., 2020; Sandwell & Schubert, 1992).

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Figure : Artemis Corona, the largest corona feature on Venus and part of Aphrodite Terra. Davaille et al., 2017 provides evidence that the south-east side of the corona is a site for subduction on Venus.

A collection of possible locations of Venus subduction have been proposed, most located along arcuate trenches that occur on the edges of some large coronae (Schubert & Sandwell, 1995). Davaille et al. (2017) observed gravity signatures that could be associated with subduction at Artemis and Quetzalpetlatl coronae. The proposed areas of subduction on Venus share many attributes with terrestrial subduction zones, such as similarities in size and a ridge-trench-outer rise pattern. The arcuate nature of trenches at some corona resembles some ocean-ocean subduction zones (Schubert & Sandwell, 1995).

If mantle plumes initiate subduction, it would occur through the delamination of the lithosphere above a shallow mantle upwelling which deforms the surface. A young thin oceanic lithosphere or a hot Venusian lithosphere would then be broken by the shallow mantle upwelling and thus initiate slab rollback subduction (Gerya et al., 2015). Slab rollback is when a portion of lithosphere sinks in the mantle, causing the trench to migrate in outboard direction. This subduction scenario has no significant lateral surface plate motion and is driven primarily by slab pull, i.e., the pulling force on the plate by a cool subducted portion of the plate. On Earth, the gravitational force of high-standing spreading ridges and the basal tractions imparted by mantle convection also contribute to the forces that drive plate motion. In each case of subduction on Earth, the overall plate motion of the down-going plate is towards the trench. The lack of significant lateral mobility of Venus’s surface implies that any subduction occurring at the coronae are most likely the product of plume-induced rollback subduction.

The proposed sequence of events creating the coronae and causing subduction start with the heating of the lithosphere above a mantle plume which causes volcanism and the weakening of the lithosphere. The volcanic loading of the surface then breaks the weakened lithosphere. The combination of the volcanic load and the weight of the lithosphere, likely assisted by the phase change from basalt into the denser eclogite (Armann & Tackley, 2012; Chapman et al., 2019; Namiki & Solomon, 1993; Piskorz et al., 2014; Rolf et al., 2018; Tsujimori & Mattinson, 2021) would increase the negative buoyancy of the slab and cause the beginning of subduction. Lastly, the trench begins to migrate back as the lithosphere continues to be pulled down (Figure 6).

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Figure : Plume induced subduction, as proposed by Davaille et al., (2017b)

### 2.5 Venus Subduction Analogs or Terrestrial Subduction

Ocean-ocean subduction zones make good analogs to subduction on Venus for a variety of reasons. First, their arcuate shapes resemble Venus’s coronae; moreover, the convex side of the arc is always the overriding plate, as would be expected for plume-induced subduction on Venus (Figure 6). Second, locations of subduction on Venus do not have a crustal plateau on one side of the trench like a continental-ocean subduction zone. Third, both plate sides are basaltic crust, which is what is expected on Venus. The terrestrial trenches that we will analyze are the: Aleutian, South Sandwich, Lesser Antilles, Mariana trenches (Figure 7).

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Figure 7: Terrestrial trenches that are analogs to Venus Subduction. The trenches are the A) Aleutian, B) South Sandwich, C) Lesser Antilles, and D) Mariana.

The Aleutian Island Arc is long volcanic arc that stretches from the Alaskan peninsula to Kamchatka. It separates the Pacific plate from the northwest portion of the North American plate, with the former subducting under the latter. The total length of the trench is ~3500 km. Pacific plate converges with the North American plate at a rate of ~50 mm/year at the eastern end of the trench and increases gradually as you move westwards along the trench (Gou et al., 2019). The South Sandwich plate is located between the South American plate and Antarctic plate. The overall plate motion of the South Sandwich plate compared to its surrounding plates is east. The westward moving South American plate brings rise to an ocean-ocean subduction zone where the young South American plate subducts under the South Sandwich plate. At this convergent plate boundary, the South American plate effectively tears allowing the subducting portion to separate from the larger northern section of the plate. The total length of the South Sandwich trench is ~750 km. The Lesser Antilles subduction zone forms the eastern boundary of the Caribbean plate (Figure 7C). Since the Eocene, the North and South American oceanic plates have been subducting westward at a slow rate of 18–20 mm/yr (DeMets et al., 2010). As the subduction becomes more oblique in the north, the arcuate slab changes from dipping to the west underneath the Lesser Antilles, to plunging to the south below Hispaniola and Puerto Rico (van Rijsingen et al., 2021). The Mariana subduction zone is formed by the older Pacific plate to the east subducts beneath the younger and less-dense Philippine plate on the west side (Figure 7D). This trench is the location of the deepest place on Earth, called Challenger Deep, that is ~ 11 km deep. All these subducting slabs have different subsurface dipping angles and depths (Figure 8).

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Figure : Terrestrial subducting slab depths dipping at complex curvatures.

### 2.6 Using Gravity to Identify Subduction

Subduction zone features should be identifiable within the gravity data, such as the subducted slab and the outer rise. However, identifying the subducted slab's gravity signature alone is complicated for a few reasons: (1) The overriding plate side of the trench (Figure 5) is more complicated and dynamic geologically. With the possibility of active mantle plumes on Venus, (2) the slab itself would start as basalt (~3000 kg/m3), which may transition into eclogite (~3500 kg/m3), and (3) the cold slab would slowly heat over time in the hotter mantle, changing the slabs thermal density.

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Figure : Bouguer Gravity Map of Venus with trench lines drawn over it. In black are proposed subduction zone trenches and in red are the larger coronae not associated with subduction.

When looking at the Bouguer gravity map of Venus (Figure 9), there seem to be low Bouguer gravity anomalies on the overriding plate side of the corona trenches associated with subduction. Because of reasons listed above, this Bouguer gravity low is not enough to confirm subduction on Venus. Alternatively, we can consider gravity gradients along a coordinate “x” that extends perpendicular to the trench and is positive toward the outboard side. Taking profiles of the ∂g/∂x Bouguer gravity gradient (i.e., the rate of change of the Bouguer anomaly per unit distance toward the outboard side) across these trenches and terrestrial analog trenches, shows a common trend at trenches associated with subduction (Figure 10). There seems to be a gravity gradient high located near the trenches of terrestrial subduction zones and proposed Venusian subduction. Using gravity gradients to look at the shallower subsurface could give a clearer insight to subduction on Venus.

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Figure : Bouguer gravity gradient profiles over Terrestrial subduction zones and Venusian coronae.

The goal of this study is to (1) fit the gravity gradient of a subducted slab with a wide range of parameters to observed gravity gradients at a variety of sites, (2) plausibly identify parameter values at sites of subduction, and (3) use misfit values to speak to the existence of subduction at this potential cites of subduction.

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# CHAPTER 3

## Gravity And Topography Data

There have been several missions sent to Venus that have collected the planet’s topography and gravity data. Until the future VERITAS and DAVINCI+ missions arrive at Venus, the most complete and high-resolution data comes mainly from the Magellan mission. The Pioneer Venus Orbiter was also used to fill in any gaps within the Magellan altimetry data producing the complete topography data product VenusTopo719 (Wieczorek, 2015). For the gravity field we used the degree and order 180 MGNP180U data product that originates from the orbital data of the same two missions (Konopliv et al., 1999).

The resolution of the gravity field is lower than that of the topography data and will prevent the study of smaller Venusian features using gravity. The gravity degree strength, ls, is the spherical harmonic degree at which the power of the gravity uncertainty surpasses the signal power (i.e., the maximum data resolution). The global power spectrum of the error in the MGNP180U gravity surpasses the power of the coefficients above degree 70, making this the nominal degree strength of the data set (Konopliv et al., 1999). This is roughly equivalent to a resolution of a 270 km spatial block. The actual degree strength varies depending on each geographic location in question, with a resolution as high as degree 100 near the equator and as low as degree 40 in some locations on the planet.

The data collection for terrestrial gravity and topography has been much more extensive, resulting in much higher resolution in the terrestrial geophysical datasets. The terrestrial topography data product used in this study is SRTMP2160, from the Shuttle Radar Topography Mission. The spatial resolution of this dataset is ~100 m. The terrestrial gravity field used was the Earth Gravitational Model 2008 (EGM2008), which is complete up to degree and order 2159 (Pavlis et al., 2012). The degree strength of this dataset is ~1700, much larger than Venus’s degree strength.

The combination of gravity and topography have been used in similar studies to understand planets’ crustal thickness, lithospheric thickness, and to model the elastic flexure of the lithosphere. In this study, we use gravity and topography to study the presence of subducted slabs in the Venus subsurface and geothermal gradients near potential subduction zones. To do this we will compare observed Bouguer gravity gradients with those predicted from a suite of forward models. We will subsequently compare the observed Geoid-topography ratios (GTRs) with those predicted from forward models of elastic lithosphere thicknesses.

# CHAPTER 4

## Methods

### 4.1 Choosing Subduction Zones

Schubert & Sandwell (1995) identified twelve locations of possible subduction zones on Venus. These locations were chosen based on topographic profiles matching lithospheric flexure signatures found on terrestrial subduction zones. When studying the degree strength of the gravity data in these locations, only five of these features are larger than their respective gravity resolutions and therefore large enough to identify within the gravity data. The four ocean-ocean subduction zones mentioned before were chosen as analogs to Venusian. Subduction: Aleutian, South Sandwich, and Mariana, and Lesser Antilles trenches. Figure 7 shows the terrestrial subduction profile paths used in this study.

The overriding plate side of both the terrestrial and Venus’s subduction zones tend to have features that are more complex to model than the outboard plate side and could cause the interpretation of the gravity on that side of the trench to be more difficult. The overriding plate side of the terrestrial ocean-ocean subduction zones might have island chains or thick sediment layers. The Venus coronae tend to have fracturing and volcanic flows on what is interpreted as the overriding plate side (Figure 5). Also, plumes could be contributing to gravity on the overriding side. To counter the problematic complex gravity signal and still be able to identify the gravity of the subducted slab, we propose the use of Bouguer gravity gradients. Gradients have shallower depth sensitivity, which at least partially mitigates the presence of deep mantle anomalies (Figure 11).

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Figure : Gravity Gradient depth sensitivity diagram (Panet et al., 2014), that illustrates the strong effect of the shallower slab on the gravity gradient.

### 4.2 Observed Gravity Gradients

Gravity gradients are used to study material in the shallow subsurface and identify sharp changes in density (Andrews-Hanna et al., 2013). The abrupt change in density across the ‘lateral’ interface between the mantle and the subducted crust would produce a gravity gradient signal that could be used to identify the presence, geometry, and characteristics of a dipping slab in the subsurface. Gravity gradients are much more effective at identifying short-wavelength features and discrete structures in the gravity data than simple gravity. This aids in filtering out the effect of any plume activity and highlights the presence of a dipping slab in the shallow subsurface.

We specifically used the Bouguer gravity gradient when analyzing both the terrestrial and Venusian subduction zones. Bouguer gravity anomaly profiles were taken across the trench from the overriding plate side to the outboard plate. The Bouguer anomaly was calculated as follows:

where FA is the Free-air anomaly, G is the gravitational constant, h is the topography and Δρ is the density contrast across an interface. On Venus this is a simple calculation because the Δρ is simply the density contrast between the atmosphere and crust. For calculating the Bouguer gravity at terrestrial ocean-ocean subduction zones, the density contrast will account for the density contrast between the atmosphere, ocean, and crust. This equation also assumes that topography is of uniform density and does not account for the presence of low-density sediment deposits that would be present at terrestrial subduction zones. The Bouguer anomaly for earth would then be calculated as follows:

where h is the seafloor topography, d is the thickness of the sediment layer and ,and are the densities of crust, water, and sediment respectfully. The sediment thickness data comes from the CRUST 1.0 model (Laske et al., 2013) and we used a sediment density of 1700 kg/m3 (Tenzer & Gladkikh, 2014). Given the low resolution of the available gravity data on Venus, for this analysis we will reduce the terrestrial gravity signal to the resolution to that of the average Venus gravity resolution. This was done using the spherical harmonic dataset to degree and order 80. The derivative is then calculated from the overriding plate and going towards the trench and outboard plate.

### 4.3 Modeled Gravity from a Subducted Slab

The bouguer gravity gradient calculated from a modeled dipping slab can then fitted to the observed bouguer gravity gradient, to identify a subducting slab in the subsurface. The gravity calculated from a simple semi-infinite dipping slab (Figure 12) is described by Telford et al., (1990),

Diagram

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Figure : Gravity calculated from a simple semi-infinite prism (Telford et al., 1990)

Using this simple model to assemble a combination of semi-infinite slabs, a more complex subduction model was made that models both the subducting crust, subducting lithospheric mantle and geothermal gradient (Figure 13). This model calculates the gravity using a crustal thickness, crustal density, mantle density, temperature contrast between the surface and mantle, dipping angle and average geothermal gradient of the lithosphere to forward model the Bouguer gravity signature at a subduction zone. We then reduced the resolution of the modeled gravity of a subducting slab to match that of the observed subduction zone gravity. This is done by using a Fourier transform on the gravity profile and filtering out the shorter wavelength features of the data. The bandpass wavelength is calculated as follows:

where R is the planets radius, and *l* is the spherical harmonic degree that the gravity signal is reduced to. Once the modeled gravity anomaly is calculated the derivative is calculated starting from the overriding plate and going towards the trench and outboard plate.

The modeled geothermal gradient is calculated based on the temperature contrast (DT) between a mantle temperature of 1400°C and the surface temperature 5°C on Earth and 475°C on Venus. The geotherm has a significant effect on the modeled gravity, for example at a higher geothermal gradient there will be hotter and less dense mantle material shallower in the subsurface. The modeled gravity from a geotherm is calculated using multiple thermal layers for different depths (Figure 13). Utilizing more thermal layers makes the model more accurate but also more computationally exhaustive. Gravity from a thermal layer is found by calculating density anomaly of each thermal layer which is described by,

Chart

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Figure : Complex subducting slab model, that includes the gravitational effect of the dipping crust and thermal lithosphere. The thermal lithosphere is calculated by splitting it up in n number of layers. Within the mantle, redder colors indicate higher temperatures and lower density.

where a is the thermal expansion coefficient of mantle, i is the index of the thermal layer in question, and n is the total number of thermal layers computed. The thermal expansion coefficient is temperature dependent and increases modestly with depth (Figure 14). The lithosphere on Earth ranges in temperatures from ~ 5 - 1400 °C and on Venus ranges from a surface temperature of ~ 475°C to an assumed upper mantle temperature of ~1400 °C. Duffy & Anderson (1989) show the temperature dependence of the thermal expansion coefficient values for the following minerals: olivine, orthopyroxene and diopside. With increasing depth within the lithosphere, the thermal expansion coefficient would increase along the plotted trend in Figure 14. Ideally the value used in our model would increase following this trend. For computational simplicity, a constant value has been used in previous modeling of the Earth and Venus’s mantle (Gerya et al., 2015; Hoggard et al., 2016). However, with the widely different surface temperatures on Venus and Earth, it is appropriate to use different thermal expansion coefficients for the two planets (See Table 1).

Chart, diagram

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Figure : Temperature dependent thermal expansion coefficient values for olivine and orthopyroxene. This figure is adapted from figure 5 in Duffy & Anderson (1989). The upper mantle of Venus and Earth will have different applicable thermal expansion coefficients.

Table : Fixed model parameters and values

|  |  |
| --- | --- |
| Fixed Parameters | Value |
| Crustal Density () | 3000 kg/m3 |
| Mantle Density () | 3300 kg/m3 |
| Sediment Density () | 1700 kg/m3 |
| Mantle Temperature | 1400°C (D. Turcotte & Schubert, 2014) |
| Earth Surface Temperature | 5°C |
| Venus Surface Temperature | 475°C |
| Thermal Expansion Coefficient | 3.0 x 10-5 K-1 (Earth)  3.5 x 10-5 K-1 (Venus) |

Table : Best-fit model parameter space explored

|  |  |
| --- | --- |
| Free Parameters | Value Range |
| Crustal thickness | 5 – 25 km (James et. al, 2013) |
| Dipping angle | 0 – 60° |
| Geothermal gradient (overriding plate side) | 2 – 30 K/km (Earth)  2 – 30 K/km (Venus) (Bjonnes et al., 2021) |
| Geothermal gradient (outboard plate side) | 2 – 30 K/km (Earth)  2 – 30 K/km (Venus) |
| Slab length | Based around the radius of corona |

For computational simplicity, our current model assumes that the subducting slab is subducting at a constant angle. This assumption simplifies the model: a more accurate representation of a subducting slab would exhibit an increasing dipping angle with depth. The subducting lithosphere is therefore a curved shape that behaves as an elastic slab that is acted on by an end load and bending moment (D. Turcotte & Schubert, 2014)). However, modeling a curved subducting slab would expand the explored parameter space. Also, assuming a subducting slab at a constant angle is sufficient for this study, as our primary goal is to detect the shallow portion of a subducted slab in the subsurface with gravity gradients. This will cause the optimization to identify the shallower dipping angles within the non-linear dipping slab. To understand the best fit model angle and depth sensitivity of our model, we ran our best fit analysis on a series of synthetic subducting slabs that change from a shallow angle to a steeper angle at different depths.

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Figure : Modeling a two-angle slab to understand the depth sensitivity of a gravity gradient (Right). Using our best fit model, we detect the shallower angle until the depth that the angle changes (D) reach to a depth of ~20 km.

We forward-modelled the gravitational attraction from a synthetic slab with two distinct slopes to understand the effects of non-linear slabs, and then we solved for best-fit angle for that subducting plate (Figure 15). The best fit analysis shows that the depth sensitivity is very shallow. The deeper angle of the two is only identified if the depth of the transition between the two angles is shallower than ~20 km. If the transition depth is in the first 250 km, then the modeled dipping angle predicts a slightly shallower angle than the actual dipping angle. So, the modeled dipping angle is sensitive to the first ~ 20-30 km and will predict a shallower angle than the observed angle. This shallow depth sensitivity is a consequence of our use of gravity gradients (Figure 11).

Once our observed gravity gradient profiles were calculated and our forward modeled slab gravity gradient profiles were created, we used optimization techniques to fit our forward model to the observed gravity gradients. This optimization was first carried out on the terrestrial ocean-ocean subduction zones previously listed, locations proposed to be subduction zones, and large coronae not associated with subduction to be used as a control group. The free parameter space explored consists of crustal thickness, dipping angle, the geothermal gradient on either side of the trench, and the slab length (Table 2). We allowed for different geothermal gradients on either side of the trench, as that is what is largely seen on Earth (Priestley et al., 2017). Two optimization techniques were utilized on our model to characterize terrestrial and Venusian subduction. First a two-dimensional grid search method was used to explore the parameter space of the model. This method assumed crustal thickness and crustal density, while exploring a wide range of values for dipping angle, slab length, and geothermal gradients. The second optimization technique utilized a particle swarm optimization that explored the parameter space of all free parameters simultaneously. For both optimization techniques we optimized for the lowest RMS misfit between the two gradients. RMS misfit function is as follows:

Diagram

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Figure : Basalt-eclogite phase diagram with geothermal gradients superimposed (James et al., 2013). The red line describes the depth that a rapidly dipping crustal slab would begin to transition from basalt to eclogite.

### 4.4 Eclogite’s Effect on Subduction

With a geothermal gradient of ~15 K/km or less on Venus, the crust could begin to undergo a phase change from basalt to eclogite (Figure 16). Also, during the initiation of slab subduction, the rapidly sinking crust could allow eclogite began to form at a shallower depth since the crust would still be at the relatively colder surface temperature. Because Venus has a hotter surface temperature than Earth, the phase change occurs at deeper depths and the solidus could prevent eclogite from forming if the geotherm is too large. The depths at which a subducting slab would be completely changed to eclogite would occur at ~50 km depth. With the shallow depth sensitivity of the gravity gradients, we do not expect our model to be sensitive the slab at this depth. However, crust could be experiencing the beginning of the transition to eclogite at shallower depths. To check for eclogite in the shallow subsurface, we ran our best fit model assuming a subducting crust made of eclogite (3600 kg/m3) and a basaltic crust containing some eclogite (3300 kg/m3). We can compare the RMS misfit values with the misfit value from the best fit that assumes a crustal density of basalt (3000 kg/m3).

Chart

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Figure : Scatter plot of the geoid and topography values for the entire surface of Venus. Topography compensated at the Moho will result in a low GTR (the slope of the green line). More dynamically compensated topography or a thicker lithosphere will result in a higher GTR (the slope of the red line) (James et al., 2013).

### 4.5 Geoid Topography Ratios

Geoid–topography ratios (GTR) are used to estimate the depths of compensation which can assist in interpreting the elastic lithosphere thickness, which can allow us to more accurately model subduction. A GTR is the least squares slope or linear regression of the geoid over the nearby topography. A higher GTR can be interpreted as being thermally compensated by mantle upwelling or a very thick lithosphere that rigidly supports a topographic load (Smrekar & Phillips, 1991). James et al., (2013) plotted the geoid and topography on the whole surface of Venus, identifying regions and their points to calculate the GTR which is the slope of the points (Figure 17). Regions like Atla and Beta Regio have some of the largest GTR values around ~20-30 m/km or higher. Since these locations are volcanic rises, it is interpreted that this topography is deeply compensated by the dynamic support of mantle plumes (Figure 18). Crustal highland regions like Maxell Montes, Ovda, and Tellus Regio all have GTR values <15 m/km. These regions all seem to have shallow crustal compensation depths meaning that isostatic compensation plays a stronger role in supporting the weight of topography in these regions.

Diagram

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Figure : GTR values for specific regions and features on Venus (Smrekar & Phillips, 1991b).

The GTR on either side of the trench should give insights to the elastic lithospheric thickness and therefore the geothermal gradient on either side of the trench. The presence of an active plume could interfere with this analysis, and in fact we expect that such a plume would have been present in the early stages of corona formation (Davaille et al., 2017b). We will use terrestrial ocean–ocean subduction zones as analogs to these proposed subduction features on Venus. On both the Venus’ and Earth’s ocean–ocean subduction zone sites we will calculate the GTR values of both sides of the trench and compare values.

In hopes to use GTR values to further understand and predict the geothermal gradient near these trenches, we forward modeled synthetic GTRs from a range of top loaded elastic lithosphere thicknesses. The GTR is theoretically related to the geoid admittance spectrum Zl by (Wieczorek & Phillips, 1997),

where is described by

and the power spectrum is

(9).

The admittance (Z*l*) is the relationship between the geoid and topography in the wavenumber domain and can be affected by the top-loading of the lithosphere or compensated deep in the subsurface by dynamic flow. A synthetic top-loaded lithosphere may be calculated using the methods from Grott & Wieczorek (2012). If the admittance from dynamic topography is Zdyn, the synthetic admittance (Zl) for a superposition of dynamic topography and top loading is a weighted average of the two admittance spectra:

where f is the ratio of topographic power associated with top loading and deep compensation. If the topographic power of top loading and dynamic topography are assumed to have a similar spectral slope for simplicity’s sake, the expected GTR for combined top loading and dynamic topography is also simply a weighted average:

We know that GTR from dynamic topography is ~40.

Similarly, the observed GTR at these subduction zone sites will be due to a combination of top loaded lithosphere and deeply compensated topography. Due to the long wavelength effect of deep subsurface compensation, the GTR on both sides of the trench will be affected nearly equally. Thus, the difference between the observed GTRs on either side of the trench will be due to differences in the elastic thickness on either side of the trench and while we cannot accurately quantify lithospheric thickness or geothermal gradient using this method, we can compare them and tell which side is larger. We will then explore the GTRs of different theoretical lithospheres to give insights into the observed GTRs at these subduction zones.

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Figure A: Terrestrial subduction zone misfits between observed data and synthetic modeled gravity using actual parameter values (Left) and best- fit solutions (Right).

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Figure B: Terrestrial subduction zone misfits between observed data and synthetic modeled gravity using actual parameter values (Left) and best- fit solutions (Right).

# CHAPTER 5

## Results

### 5.1 Terrestrial Subduction Zone Misfit

In the process of fitting the gravity gradient from a modeled subducting slab to the observed terrestrial Bouguer gravity gradients, we want to quantify the difference between the best-fit solution and the actual known values for these subducting slab variables. This will establish a threshold of what will be considered a good fit when applying the best-fit model to Venus’s subduction zones. To do this we compared the best-fit solution RMS misfit values with the RMS misfit based on known input variables of that subduction zone. The known dipping angle used came from the average dipping angle down to a depth of 100 km (Figure 8) and geothermal gradient comes from lithospheric thicknesses. Comparing these two RMS misfits helps us understand the acceptable range of RMS values and account for overfitting that may cause the best fit solution to vary from the actual (Figure 19). There is an ~0.3 Eötvös RMS difference between the best fits and actual value misfits. Therefore, when we attempt to model subduction zones on Venus for which the true slab parameters are unknown, we will consider ~0.3 Eötvös to be a plausible level of misfit.

When comparing the accuracy of the best-fit solution values for dipping angle and geothermal gradient, we find that the interpreted dipping angle’s accuracy varies within a wide but acceptable range. This wider range is due to the limitation of fitting a synthetic gravity gradient signal of a linear slab to that of an actual subducting slab dipping at an angle that increases with depth. However, the best-fit geothermal gradient values align well with the actual values with an average percent error of 6%. The RMS best-fit misfit values for these terrestrial sites range from 0.06-0.5 Eötvös. See Table 3 (blue) for best-fit model parameters and values.

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Figure : (Left) RMS misfit plots of Artemis (Top) and Quetzalpetlatl (Bottom). (Right) Grid search of geotherms on both sides of the trench. Notice that for both trenches, the grid search of geotherms show a best-fit with a higher overriding plate geotherm. This is consistent with a thinner lithosphere.

### 5.2 Potential Venus Subduction Zones and Coronae Misfits

Performing this model optimization on both trenches associated and not associated with subduction resulted in distinct results. For the locations associated with subduction (Table 3 in orange), either there was a good fit with a low RMS misfit and the best-fit values for angle and geothermal gradient or the RMS misfit was higher, and the subduction angle was very low. All but two of these sites had an RMS misfit < 0.1 Eötvös. For the other Coronae not associated (Table 3 in yellow), the misfit was also high with the angle mostly optimized close to zero. The best-fit geotherms shows a trend of a higher overriding plate geotherm at terrestrial and Venus’s subduction zones. The average slab density for these best fits show that the terrestrial subducting slabs are denser than the surrounding mantle by ~100 kg/ m3. The Venus sites that appear to be subducting slabs also have a positive density anomaly but around ~70-90 kg/ m3.

Table : Best-fit Model results for Venus possible subduction zones (orange), corona not associated with subduction (purple), and terrestrial ocean-ocean subduction zones(blue). GTR calculates for Venus possible subduction zones and terrestrial ocean-ocean subduction zones. For terrestrial geothermal gradients, the actual observed values based on lithospheric thickness calculations (Priestley et al., 2017) are in parenthesis.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Site | RMS Best-fit Misfit  (Eötvös) | Best-fit Angle  (°) | Best-fit Overriding Plate Geotherm (K/km) | Best-fit Outboard Plate Geotherm (K/km) | Overriding Plate GTR (m/km) | Outboard Plate GTR (m/km) | Average Slab Density (kg/m3) |
| Venus: |  |  |  |  |  |  |  |
| Artemis | 0.07 | 41 | 8 | 7 | 11 | 43 | 3370 |
| Quetzalpetlatl | 0.09 | 48 | 5 | 4 | 13 | 33 | 3389 |
| Atahensik | 0.74 | 4 | 2 | 15 | 13 | 40 | 3359 |
| Nightingale | 0.06 | 1 | 3 | 15 | 7 | 15 | 3323 |
| Astkhik Plateau | 0.05 | 58 | 10 | 7.5 | 10.5 | 19 | 3385 |
| Uorsar Rupes | 1.34 | 6 | 15 | 7 | 5 | 10 | 3335 |
| Dunne-Musun | 0.32 | 1 | - | - | - | - |  |
| Heng-O | 0.64 | 58 | - | - | - | - |  |
| Bau | 1.04 | 1 | - | - | - | - |  |
| Nabuzana | 2.40 | 1 | - | - | - | - |  |
| Earth: |  |  |  |  |  |  |  |
| Aleutian | 0.06 | 41 | 20 (21) | 15.5 (15) | 3 | 5.3 | 3403 |
| Sandwich | 0.3 | 75 | 29 (24) | 13 (13) | 0.9 | 3.8 | 3411 |
| Mariana | 0.50 | 70 | 29 (28) | 16 (13) | -0.5 | 4.5 | 3401 |
| Lesser Antilles | 0.22 | 29 | 17 (16) | 13 (14) | -1.2 | 3.7 | 3408 |

Table 4: Modeling subducting slabs at Artemis Corona using different amounts of eclogite and therefore densities.

|  |  |
| --- | --- |
| Subducting Crust Density (kg/ m3) | RMS Misfit Values  (Eötvös) |
| 3000 | 0.09 |
| 3300 | 0.29 |
| 3600 | 0.26 |

### Chart Description automatically generated5.3 Presence of Eclogite Explored

For Artemis Corona, we performed our best fit model assuming three different compositions and densities for the subducted slab: basalt (3000 kg/m3), mix of basalt and eclogite (3300 kg/m3), and eclogite (3600 kg/m3). This was done to explore the possibility of eclogite existing in the shallow subducted slab. When comparing the misfits, we see that the fit assuming basaltic crust has the lowest RMS value (Table 4 & Figure 21). This is consistent with our assumption that the gravity gradient is not sensitive to any eclogite in the subducting slabs.

Figure 21: RMS misfit plots assuming a dipping crustal slab of basalt (top), basalt & eclogite (middle), and solely eclogite (bottom).

### 5.4 Observed and Modeled Gravity Topography Ratios

For the terrestrial subduction zones and the Venus subduction zones, GTR values were calculated on both sides of the trench (Table 3). When comparing GTR values of both sides of the trench at the same location, we see that the outboard plate is significantly higher. This is true for both terrestrial and Venusian trenches. The modeled or synthetic GTR values for a top-loaded lithosphere and subsurface compensation (Figure 22) shows that, no matter the subsurface interaction, a larger GTR means a thicker elastic thickness (Table 5). The GTR over terrestrial oceanic plates tends to range between -2 and 6 m/km while GTRs on Venus range between 5 and 43 m/km. The difference between terrestrial and Venusian GTR ranges can be explained by the contribution of mantle dynamic flow.

Chart, line chart

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Figure : Geoid admittance spectra of top-loaded lithospheres of different elastic thicknesses.

Table 5: Modeled GTR values for top-loaded (f = 0) lithospheres of different elastic thicknesses and a combination of top-loading and deep subsurface compensation (f = 0.5). Note that GTR trends upward as lithospheric thickness increases.

|  |  |  |
| --- | --- | --- |
| Elastic Lithosphere Thickness (km) | Modeled GTR (m/km): (f = 0) | Modeled GTR (m/km): (f = 0.5) |
| 0 | 3.6 | 21.8 |
| 5 | 4.9 | 22.5 |
| 10 | 6.3 | 23.1 |
| 20 | 9.1 | 24.6 |
| 30 | 12.1 | 26.0 |
| 50 | 17.7 | 28.9 |
| 70 | 23.0 | 31.5 |
| 100 | 30.0 | 35.0 |

# CHAPTER 6

## Discussion

### 6.1 Geothermal Gradient on Venus

An important trend seen in the actual observed geothermal gradient values on Earth, is a larger geotherm on the overriding plate side. This trend is also seen in the best-fit modeled data for terrestrial subduction zones and most of the potential Venusian subduction zones. The two that this trend does not hold for are Nightingale and Atahensik Corona. These two sites also have best fit dipping angles close to zero. These two discrepancies could indicate there is no subduction, or the best-fit solutions are overfitting and do not best describe the actual subsurface geology in these areas.

The GTR observed values show a trend inverse that of the geotherm, with a lower GTR on the overriding plate. This agrees with the forward modeled GTR values for a top-loaded lithosphere (Table 5), which shows a trend of increasing GTR with increasing lithosphere thickness. With geothermal gradients being inversely proportional to lithospheric thicknesses, these lower GTRs on the overriding plate side suggest a thinner lithosphere. Both the GTRs and Modeled geothermal gradients identify a trend of the subducting slab and outboard plate side being of a thicker lithosphere and smaller geothermal gradient. This is what we would expect based on what we know from terrestrial subduction, a thicker and colder lithosphere subducting under a hotter and thinner lithosphere. We would also expect a smaller GTR and larger geotherm over the center of a coronae, were the lithosphere would be younger or thinner due to interactions with the mantle plume that created it. This is further evidence that these locations are plausible locations for subduction on Venus. The modeled terrestrial geotherm values being within an average percent error of ~6%, we can trust the modeled geothermal gradients of those best-fits RMS misfits below ~0.5.

### 6.2 Subduction on Venus

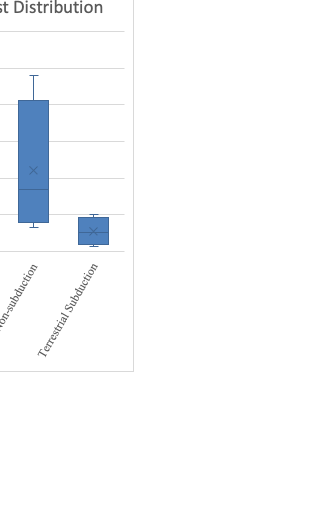
When analyzing the Bouguer gravity gradient best-fit model results, we first use the terrestrial subduction zones as analogs to compare to those on Venus (). All the terrestrial RMS misfit values were below 0.5 Eötvös and with believable best-fit values for dipping angle, slab length and geothermal gradients. This analysis gives us reasonable certainty that we are detecting the gravitational effect of a subducted slab in the subsurface. The terrestrial RMS misfit values tend to be slightly larger than those of Venus, and this is likely because when subtracting sediment layers from the gravity signal, we assumed a constant sediment density of 1700 kg/m3. On Venus there were observed to be two types of study areas: previously proposed subduction sites (both coronae and non-coronae related trenches) and large corona not thought to be associated with subduction. The later can be seen as a control group to compare with the proposed subducting trenches. At first glance at the RMS values for the three different sites, the Venus and terrestrial subuction zones have lower misfits than the non-subduction Venus trenches. The non-subduction Venus sites seem to have either or both RMS Values above 0.5 Eötvös and dipping angles that are optimized at angles close to zero. Both these results point at the unlikelihood of a subducting slab in the subsurface. Looking at the proposed subduction zone sites, we evidence in favor of subducting slabs at some of the sites. Nightingale Corona while having a low RMS, has a near zero dipping angle. This could indicate the presence of a subducting slab but just at a low angle. It is likely that the modeled angle of 1° is an underestimation of the actual angle because of the linear slab model. Atahensik and Uorsar Rupes also have higher RMS values and low dipping angles. This means that there is low likelihood of a subducted slab in these locations. However, Artemis, Quetzalpetlatl, and Astkhik Plateau have strong fits with dipping angles and geothermal gradient that a further support the present of a subducting slab in the subsurface.

Figure : RMS misfit distribution between types of trenches. Note that both terrestrial and Venusian subduction zone locations have low RMS misfits to fitting a subducting slab to observed gravity.

### 6.3 Slab Buoyancy

In addition to this study showing evidence of subduction on Venus, the best-fit models give us an insight to the buoyancy of the slabs at each trench. At the terrestrial subduction zones, the slabs are negatively buoyant and ~100 kg/ m3 denser than the surrounding mantle. The Venus subducting slabs are also negatively buoyant but are only ~70-90 kg/ m3 denser than the mantle. This small difference could be the reason we do not see plate tectonics and continuous subduction on Venus. On Earth, the negatively buoyant slab pulls on the plate (slab pull) and is a large driving force in plate tectonics and recycling the crust. However, the descending slab only pulls a single plate down with it. The lack of plate tectonics on Venus might be the reason that the negatively buoyant force is not causing surface motion. This leads to the questions of what magnitude of negative slab buoyancy is necessary to first initiate and second continue driving subduction? What effect does the tectonic plate size or subducting slab play in surface motion? These questions will improve our understanding of plate tectonics and subduction initiation.

The smaller slab densities on Venus, like the smaller geothermal gradients, are likely due to the smaller temperature contrast between the mantle and surface. This implies that surface temperature might have a more important role in surface mobility and tectonic regimes than previously speculated. While data including surface mobility on exoplanets may be a long time coming, Venus could be our first insight into hot exoplanets and how surface motion occurs on hot exoplanets.

In summary, there appear to be at least ways in which temperature affects the buoyancy of a subducting slab on Venus and other hot Earth-like planets. Firstly, if higher surface temperatures are not matched by higher mantle temperatures, a diminished temperature contrast in the lithosphere will reduce the negative buoyancy of the slab. Secondly, higher temperatures will increase the depth of basalt stability, inhibiting the formation of eclogite and reducing the negative buoyancy (Figure 16). Finally, the temperature-dependence of the thermal expansion coefficient will lead to a modest increase in the negative buoyancy of the slab. As demonstrated by the slab density estimates in Table 3, the net effect of these considerations is a decrease in the downward pull of a subducting slab on Venus.

### 6.3 Implications for VERITAS mission

Sometime in the late 2020’s NASA will be sending a mission to Venus called VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy). On board it will contain synthetic aperture radar, emissivity mapper, and will perform radio science to improve the gravity data. Improved radar mapping and gravity of Venus will give us higher resolution images, topography, and gravity data for the locations looked at in this study. This will get us more accurate best fits from our optimization model. This will also open the door to studying smaller features that are thought to have subduction occurring at them (ex. Eithinoa Corona, Atete Corona, Neyterkob Corona, Demeter Corona, and Hecate Chasma), but the current gravity resolution limits our analysis. Once VERITAS data is received, it will be worth applying these methods to more coronae on Venus that are currently too small for such modeling.

VERITAS will improve the resolution of the observed gravity data and increase the nominal degree of spherical harmonics from 70 (270 km) to around 130 (145 km). This increased resolution should decrease the RMS uncertainty in our values for the fitted or modeled subducting slab. To show this, we performed a grid search fitting our subducting slab model to a synthetic slab at both resolutions and calculated the misfit (Figure 24). The RMS misfit and variable range is dramatically narrowed just by improving the degree strength from 70 to 130. The RMS angle parameter narrowed by a factor of ~1/2. The RMS optimization narrowed as well for the Geothermal gradient.Diagram

Description automatically generatedDiagram

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Figure : Grid search of a known synthetic slab using degree strength 70 (Top) and 130 (Bottom) to compare RMS improvement with improved degree strength. Note that for higher degree strength, the RMS misfit contour map tightens around the true value.

We used Bouguer gravity gradients in our study because of their sensitivity to the shallow portions of a slab, which helped ignore the effect of plume activity and eclogite to identify subduction. However, with the VERITAS gravity data resolution, this method could be used with the Bouguer gravity and include the effect of a basalt-eclogite phase change on the subducted slab. The best fit would then tell us whether eclogite is present in the subducted slab and at what depth. Whether eclogite is detected could tell us more about subduction initiation on Earth and Venus.

Additionally, the calculation of Bouguer gravity requires a crustal bulk density estimate to remove the effects of gravity from topography. In this study a value 3000 kg/m3 is assumed for the crustal density, based on our limited understanding that much of the surface is basaltic. The actual density of topography likely varies within a few hundred kg/m3, or greater if felsic material exists on Venus. Rock composition likely plays a larger role in bulk density as surface temperature should limit the surface rock’s pore space. The emissivity mapper onboard VERITAS will improve our understanding of the surface composition and further constrain the crustal bulk density and how it varies globally.

More accurate bulk density calculations can also be made in various locations on Venus using the Nettleton’s Method(Nettleton, 1939). If there is a varying amount of topography, Nettleton’s Method estimates the bulk density of the crust through a simple least-squares regression between the observed gravity and the gravity expected from topography (Figure 25). The expected gravity from Venus’s topography is estimated using the calculation described in Wieczorek & Phillips (1998). The uncertainty in bulk density calculation at the current gravity resolution of 70 degrees is ~450 kg/m3 and at the VERITAS resolution of 130 degrees is ~300 kg/m3 (Dame, 2020).

Chart, scatter chart

Description automatically generated

Figure : Least-squares regression between the observed gravity and the expected gravity of Haastse-baad Tessera (assuming a ρ = 1 kg/m3) with the slope being equal to a bulk density of 2930 kg/m3

# CHAPTER 7

## Conclusions

In this work we use two different gravity metrics to both identify subduction and quantify geothermal gradients on Venus. We applied these methods to terrestrial subduction zones and locations on Venus both associated and not associated with subduction. There are three main findings from this study. (1) Our modeled results are consistent with subduction in at least three locations on Venus: Artemis Corona, Quetzalpetlatl Corona, and Astkhik Plateau. These subducting slabs were found to be denser than the surrounding mantle as expected, but the density contrasts associated with these slabs were less than those of Earth’s slabs. (2) We also have identified a trend at terrestrial and Venusian subduction zones of a higher geothermal gradient on the overriding plate side of the trench and a lower geothermal gradient on the outboard side. We would expect to see this based on our understanding that an older, thicker, and colder (i.e., denser) lithosphere will subduct under the younger, thinner, and hotter (i.e., less dense) plate. The estimated values for the geothermal gradients at these locations ranging from 4 – 10 K/km. (3) The subducting slabs on Earth and Venus are negatively buoyant. However, the Venus slabs tended to be slightly less negatively buoyant. These methods can be reproduced on any subduction zone trench and should be repeated for smaller corona once VERITAS’s gravity data has been recovered.

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