Habitability, Geodynamics, and the Case for Venus

Primary author: Suzanne Smrekar
Jet Propulsion Laboratory/California Institute of Technology, Pasadena CA ssmrekar@jpl.nasa.gov, *818-687-7926*

Co-authors: Jeff Andrews-Hanna (U.AZ), Doris Breuer (DLR Berlin), Paul Byrne (NCSU), Debra Buczkowski (JHU/APL), Bruce Campbell (Nat. Air Space Museum), A. Davaille (CNRS/U. Paris-Saclay), Darby Dyar (Mt. Holyoke/PSI), G. Di Achille (INAF/Astro Obs. Teramo), Caleb Fassett (Marshall), Martha Gilmore (Wesleyan), Robert Grimm (SWRI), Jorn Helbert (DLR Berlin), Scott Hensley (JPL), Robert Herrick (U. Alaska), Luciano Iess (U.Roma), Lauren Jozwiak (JHU/APL), Tiffany Katiaria (JPL), Marco Mastrogiuseppe (U. Roma), Erwan Mazarico (Goddard), Nils Mueller (DLR Berlin), Daniel Nunes (JPL), Joseph O'Rourke (ASU); Patrick McGovern (LPI), Maria Raguso (Caltech), Joann Stock (Caltech), Constantine Tsang (SwRI), Thomas Widemann (Obs. Paris), Jennifer Whitten (Tulane), Thomas Widemann (LESIA), Howard Zebker (Stanford)

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Introduction

A deep understanding of how planets support life requires identification of the key factors and a model of how they control a body's environment over time. A planet's geodynamic evolution describes the processes that link its interior heat engine and volatile reservoir to geology and surface/atmospheric volatile inventory over time, which ultimately determines habitability. Both the NASA Astrobiology Strategy [1] and NASA's Exoplanet Strategy agree on probable key factors governing habitability: surface oceans, a stable secondary atmosphere (likely dominated by volcanic outgassing), a sufficient internal energy budget to drive tectonic/volcanic activity and weathering to replenish the atmosphere, a magnetic field, and feedback among these processes. Earth's overarching geodynamic process, plate tectonics, has shaped its long-term habitability. A major question for understanding Earth's evolution, and one that may influence habitability on exoplanets is what are the conditions that enable plate tectonics?

Although supremely unhospitable to life today, Venus's geodynamic similarities to Earth provide the ultimate control case for understanding rocky planet evolution and habitability (e.g., [2]). It very likely had past long-term surface water, as well as a dynamo. Tectonism and volcanism, with associated outgassing, likely persist today. A majority of rocky Earth-sized exoplanets lie in the high insolation "Venus-zone" [3]. The ultimate question is are any of them habitable? Although hellish today, Venus may well have been the first habitable planet in our solar system [4, 5]. There are a number of scenarios for the loss of liquid water on Venus; an understanding Venus' geologic evolution is one of the key unknowns [6]. The search for 'Earth 2.0', a potentially habitable exo-planet, will always be based on a small number of observable parameters: size, density, insolation and limited upper atmospheric chemistry. Well-validated models are the only means of predicting surface environment. Without a comprehensive understanding of the evolutionary history and divergence of Venus and Earth, models of habitability (e.g., [7]) cannot be validated. Such models require a better understanding of Venus' geodynamics. In particular, why doesn't Venus have plate tectonics like Earth?

Plate tectonics and its role in habitability. Earth's long-term temperate climate and habitability is strongly influenced by its geodynamic system of plate tectonics [8, 9]. Over much of Earth's history, plate tectonics has been the driving force for volcanic activity, bringing new rock to the surface to fuel chemical reactions and release volatiles into the atmosphere. As temperatures rise, more CO_2 dissolves in the oceans and precipitates out, creating a climate feedback system. Subduction, the process by which a tectonic plate is carried into the mantle, plays a key role as it recycles volatiles into the mantle, which can be re-released via volcanism. A major question for understanding Earth's evolution, and one that may influence habitability on exoplanets is what are the conditions that enable plate tectonics? Specifically, how does subduction start?

The start of plate tectonics on Earth is highly debated, but may have been as early as 4 Ga. Data on this are limited, and criteria such as the chemistry and volume of continental crust over time are used as proxies for the start (e.g., [10]). Subduction is believed to be both the first step in initiating plate tectonics, and necessary for forming massive amounts of felsic (low iron) crust. Partial melting of basalt can produce small volumes of felsic rock, as seen on Mars [11] and the Moon [12], but water and crustal recycling via subduction (or possibly delamination) are needed to produce the massive volume of Earth's continents [13]. Erosion of continental crust into the oceans provides important nutrients for life. The growth of continental crust may have produced Earth's great oxygenation event [14]. Thus, determining if Venus' tessera plateaus, defined by their intense, multidirectional deformation structures, are mafic (high iron, and thus likely deformed volcanic plains) or felsic is a key constraint on the history of water and habitability.

Beyond Earth, only Venus is likely to have both current subduction/lithospheric delamination, and huge plateaus of possible felsic crust. A deep understanding of Venus' geodynamics could constrain the conditions needed for both subduction and the formation of evolved felsic crust [15] – both of which may be fundamental to rocky planet habitability.

Recent Advances: Dispelling Myths about Venus

NASA's Magellan mission, launched in 1989, was the last to study Venus' surface. It resulted in revolutionary new theories about rocky planetary evolution. In the absence of new data, these decades-old ideas have been codified in textbooks and in collective thinking, effectively becoming myths. However, new data and theories constraining the origin and evolution of solar system volatiles and revitalized Venus studies shine a new light on many of these old ideas.

Myth 1: Venus Is Geologically Dead

Venus has a youthful surface. Unlike Mars, Mercury, and the Moon, Venus lacks large impact basins. If corrected for the presence of water in its oceans, Earth would have roughly a similar number of impact craters to Venus. Clearly, erosion and deposition have effectively erased many impacts on Earth. On Venus, the primary forces are volcanism and tectonism, and thus craters are a more direct measure of interior vigor. The average age is usually given as 700 ± 300 m.y. (e.g., [16]). However, new ideas on impactor origins imply a much younger age, potentially less than 250 m.y. [17, 18].

Despite these new ideas, the popular view of Venus that appears in many textbooks reads something like "Venus resurfaced 350-750 m.y ago". The idea of one-time 'catastrophic resurfacing' is based on two observations: 1) the ~1000 craters with latitudes and longitudes that are indistinguishable from a random distribution [16], and 2) the fact that only ~10% of craters are conspicuously modified by volcanism or tectonism [19]. This catastrophism concept has captured public and scientific imagination (e.g., [20]), leading to the idea that Venus might undergo episodic plate tectonics, oscillating between a past mobile lid that produced massive resurfacing and a geologically quiescent stagnant lid (e.g., [21] and many subsequent papers). Similarly, the ~1 km global blanket of volcanism needed to wipe out prior impacts would outgas volatiles capable of creating enormous climate change [22], with temperatures swings large enough to cause surface deformation [23].

However, equilibrium resurfacing models fit the impact crater data equally well [24, 25], especially when their extended ejecta [26, 27] and dark-floored (radar smooth) craters [28] are considered. Non-catastrophic Monte Carlo models can replicate random spatial distributions [29], but they initially over-predicted the fraction of embayed craters [30]. These models were tuned to yield the correct proportion [24], but not the random distributions of embayed craters. A new class of Monte Carlo models, featuring thin flows instead of shield volcanos predominantly, can explain the spatial and size distributions and relative frequencies of dark- and bright-floored craters using equilibrium resurfacing [25]. The true fraction of embayed craters is ~80% if craters with radar-dark floors are volcanically modified, implying an average surface age as low as 150 m.y. [28]. Both aeolian weathering and volcanism/tectonism can remove fine-grained ejecta deposits, but only volcanism/tectonism can remove craters. Analysis of these considerations show that Venus has both young, geologically modified areas and old areas dominated by aeolian removal of ejecta that are not craters [26]. This demonstrates Venus' surface is not uniform in age. Additionally, Venus' center-of-figure to center-of-mass offset is inconsistent with global lithospheric overturn in the last ~2 b.y. [31].

New evidence for an active planet. Visions and Voyages (2011) called out the discovery of recent volcanism on Venus [32] as one of a dozen major achievements in planetary science over the past decade. The VIRTIS instrument on Venus Express provided surface emissivity for ~25% surface coverage with adequate SNR. Smrekar et al. 2010 interpreted high emissivity regions as evidence for recent, unweathered basalt, corroborated by evidence for a mantle plume at depth based on Magellan gravity and topography data. Venus Express also recorded evidence of variable SO_2, likely due to volcanic outgassing [33].

<u>Needed data:</u> Current resolution does not permit an assessment of what processes are removing craters and their extended ejecta. For example, even stereo topography is marginal for showing external volcanism [28]. High resolution topography of all craters—including potentially yet to be discovered craters in the deformed tesserae—is needed to assess the integrated resurfacing history of Venus (Figure 1).

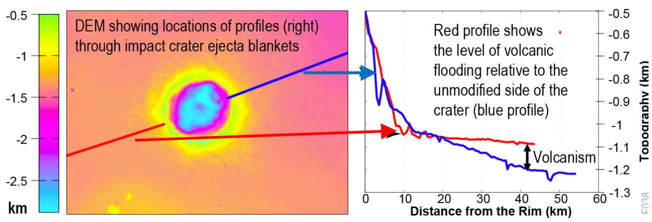

Fig. 1. High res. topo reveals volcanic flooding of impact crater exteriors. Left: LOLA DEM for the lunar crater Euler, which was volcanically flooded. Right: Topo. profiles have 10 m height accuracy, 500-m horz. postings. The red line shows a profile through a flooded region outside the crater; blue shows an area without flooding.

Myth 2: The Interior of Venus is Dry

Many papers have advocated that a dry interior is responsible for differences in the evolution of Venus and Earth, and in particular for Venus' dearth of plate tectonics (e.g., [34]). Venus appears to lack a similar upper mantle low viscosity zone (LVZ), based on gravity and topography analyses [35]. Given Venus' very high surface temperature, a wet lithosphere would be extremely weak. The presence of high topography and mildly relaxed impact craters suggest dry crust/lithosphere [36, 37]. However, a dry atmosphere and crust/lithosphere need not imply a dry mantle. Most papers advocating a dry Venus were written when comets were believed to be the dominant source of planetary volatiles. New measurements of cometary volatiles indicate that they constitute <5 % of Earth's water [38]. Instead, planetesimals carry the bulk of a planet's volatiles, which are released into the atmosphere over time via volcanism. Evidence that Earth's deep mantle holds significant water [39], despite a long history of plate tectonics, further solidifies this idea.

Venus' interior is likely to retain significant water [40]. Venus' Ar isotope data suggest about 25% of Venus volatiles have outgassed compared with ~50% of Earth's [41, 42]. Indeed, it is difficult to fully desiccate Venus [43], although in theory early magma ocean processes could do so [44].

Does Venus have 'continents'? On Earth, continents form when basalt subducts or drips into the mantle and melts in the presence of water. Although other processes can form the low iron, high silica felsic rock that forms continents, they cannot produce the massive volume of Earth's continents. Tesserae—highly deformed regions that cover 7-8% of Venus' surface—may be the Venusian version of continents. Most tesserae occur as high standing, isostatically compensated plateaus 1-2000 km across, with small 'inliers' embayed by regional plains. One such plateau, Alpha Regio, was observed by VIRTIS. Its emissivity is consistent with a felsic composition [45, 46].

Could Venus still be outgassing water? The observed pyroclastic flows require significant volatiles (e.g., 4-5 wt% of H_2O and/or CO_2) to overcome the ambient surface pressure [47], similar to the volatile content of some terrestrial volcanoes. Although challenging, detection of volcanically outgassed water would be game-changing, definitive proof of present day interior water.

Needed data: Although the Venus Express VIRTIS data provided a proof of concept for NIR spectroscopy of the surface using a single wavelength for observations, a spectrometer designed for the Venusian surface could observe in 6 bands near 1 micron (a region dominated by iron signatures) at much higher SNR. Such data would provide a definitive test of abundant felsic crust [48], as well as possible variations in iron content of surface rocks. Such a spectrometer could also search for near-surface water vapor and active/recent volcanism. See [49] and the Decadal Survey White Paper by Dyar et al. for details of the valuable compositional information and methodology of orbital spectroscopy on Venus.

Myth 3: Venus Lacks Plate Boundaries

Venus has enormous and complexly deformed tectonic features. Yet the link to mantle processes for most features remains obscure. There is no evidence of an Earth-like network of plates. However, there *is* evidence for roll-back subduction [50] [51]. Others interpreted some of these features as mantle plumes [52]. New work, motivated by the quest to understand initiation of subduction on Earth [53], provides a robust interpretation of these features as plume-induced subduction [54]. The presence of subduction, widely believed to be the first step towards plate tectonics, makes the lack of plate tectonics on Venus even more enigmatic. What conditions allow subduction but not plate tectonics [55] [54]? Answering this question is extremely important for understanding the initiation of plate tectonics on Earth and exoplanets.

Venus is too dry? For decades, Venus' lack of plate tectonics was attributed to a dry interior (e.g., [34]). Water is a key ingredient in mantle and lithospheric rheology. It may (or may not, c.f. [56]) be responsible for the LVZ beneath Earth's oceanic lithosphere, which is believed to facilitate plate motion [57]. Venus' dry crust may inhibit the formation of weak zones that enable plate tectonics [58].

Is Venus too hot? Alternatively, Venus' high temperature may inhibit plate tectonics. Venus' lithosphere has been proposed to be too weak to support plate formation [21]. Shear-heating induced localization becomes less likely in a hot lithosphere [59]. Additionally, perhaps lithospheric-scale faults form but cannot be maintained long enough for an organized set of plates to develop. Faults anneal more quickly at high temperature via mineral growth [60] [61]. Moreover, high temperature precludes strong dynamic weakening in friction [62]. Alternatively, hot surface temperatures and a stagnant lid may result in a hot mantle with insufficient stress to break the lithosphere [63].

Needed data: Current data do not offer a full view of Venus' tectonic system. It is entirely possible that major plate boundaries/shear zones are invisible in current data (Fig. 2). High resolution topography and radar imaging is needed to fully understand Venus geodynamic system. Gravity data would provide key information on global lithospheric thickness, and the first ever constraints on core size, a key unknown in understanding why Venus currently lacks a magnetic field.

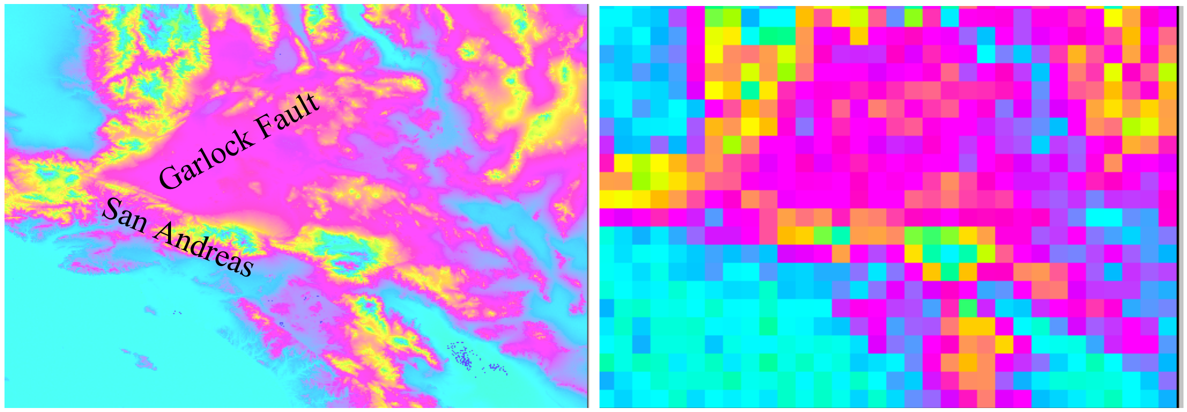

Fig. 2. High resolution topography could discover narrow deformation zones such as strike-slip plate boundaries not apparent in image data. SRTM topo data (blue= low, purple = high), reduced to VERITAS (see below) resolution (left, 240-m horz. 5-m vert. noise) clearly plate boundaries and major faults. Such faults are invisible at Magellan resolution (right, 15-km horz. 100-m noise).

Emissivity, Radio science, InSAR, Topography And Spectroscopy (VERITAS) is a proposed Discovery Mission designed to dispel the three myths of Venus science, and much, much more.

Myth 1*: "Rumors of Venus' death have been greatly exaggerated!"*

i) *Resurfacing (or volcanism vs. impacts)*

- high resolution topo to asses internal and external volcanic flooding of craters
- medium-high resolution image data to examine processes erasing extended ejecta

ii) *Search for current geologic activity*

- Near-IR spectroscopy for recent or active volcanism.
- Repeat pass interferometry for surface deformation
- Surface change via comparisons to prior missions: Magellan radar, VIRTIS emissivity

Myth 2: *Evidence of past and present interior water?*

- Near-IR emissivity plus high resolution topography of ~1 km scale features - surface temperature as f(elevation) must be removed- to determine if tesserae are felsic
- Near-IR spectroscopy to detect near surface water vapor anomalies

Myth 3: *Geologic evolution: why has plate tectonics not evolved? Did it in the past?*

- High-resolution topography, gravity, imaging, deformation, near-IR spectroscopy to study subduction
- Global high-resolution topography and gravity to look for buried features (e.g., as observed on Mars) and look for unrecognized deformation
- Global improved gravity field to estimate elastic thickness, a proxy for heat flow
- Integration of all of the above to determine how and why Venus and Earth diverged

Instrument Innovations Enabling VERITAS

Innovation in SAR interferometry developed for Earth and a spectrometer designed to peer through Venus' atmosphere provide elegant solutions for creating a broad range of essential new data. Just two instruments and a radio science experiment will reveal an entirely new planet.

Venus Emissivity Mapper (VEM) [64]

- First-ever spectrometer designed to provide multichannel spectra with high SNR for the surface of Venus.
- Supported by growing laboratory spectral library acquired at Venus temperature (pressure is unimportant for emissivity).

Venus Interferometric Synthetic Aperture Radar (VISAR) [65, 66]

- Real-time processing hardware advances (FPGAs, memory, etc.) enables onboard processing and thereby high-resolution global coverage of surface.
- InSAR algorithm advances and information extraction for interferometric data enable global topographic measurement and the search for active surface deformation.
- Magellan derived gravity fields allows improved mission planning and orbit reconstruction for accurate targeting of repeat pass interferometry.

Gravity Science

- NASA's Deep Space Network has committed to Ka-band communications, permitting high precision two-way Ka-band doppler data to greatly improve global resolution, enabling global elastic thickness estimates and the first bounds on core size, a critical constraint on understanding why Venus currently lacks a magnetic field.

VERITAS Would Advance Understanding of Habitability and Enables Future Venus Missions

VERITAS would reveal Venus' surface geochemical and tectonic history. These goals directly access the building blocks of planetary habitability— the history of volcanism and volatile outgassing from the interior, crustal recycling and formation of crust in the presence of water, past tectonic/ convective history, current elastic thickness/heat flow, and implications for a past magnetic field. These factors, and their comparison to between Venus and Earth, are essential to models that aim to predict exoplanet habitability. In addition to fundamental science, VERITAS data will provide state-of-the-art global reconnaissance information including 250 m horz. by 5-m vertical resolution topographic map covering >95% of the planet, the first ever maps of igneous rock type, surface oxidation, and volcanic/tectonic activities. These data are critical to maximize the value of new approaches for in-situ measurements that are being explored, from geochemical landers to rovers. It would be a scientific travesty to invest in costly surface investigations without first conducting state-of-art global reconnaissance, including the first ever maps of igneous rock type, surface oxidation, and volcanic/tectonic activity. The charge from Visions and Voyages was to select missions that provide the most science per dollar, and which offer balance across the solar system. The proposed VERITAS mission follows up on recent discoveries at the heart of planetary habitability: recent volcanism on Venus, a mechanism for initiation of plate tectonics on Earth, a new understanding of volatiles throughout our solar system, and hundreds of 'exo-Venuses' in other solar systems. VERITAS promises enormous science value per dollar, and fills the gaping hole in comparative planetology created by ignorance of Earth's sister planet.

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