At the VEXAG meeting in November 2017, it was resolved to update the scientific priorities and strategies for Venus exploration. To achieve this goal, three major tasks were defined: (1) update the document prioritizing Goals, Objectives and Investigations for Venus Exploration, (2) develop a Roadmap for Venus exploration that is consistent with VEXAG priorities as well as Planetary Decadal Survey priorities, and (3) develop a white paper on technologies for Venus missions. Here, we present the Goals, Objectives and Investigations for Venus Exploration.

Prepared by the VEXAG Goals and Exploration Sites Focus Group: Allan Treiman (Chair), Giada N. Arney, Lynn Carter, James Head III, Candace Gray, Stephen Kane, Kevin McGouldrick, Laurent Montesi, Joseph O’Rourke, and Chris T. Russell.

Introduction

Venus and Earth began as twins. Their sizes and densities are nearly identical and they stand out as being considerably more massive than other terrestrial planetary bodies. Yet the Venus that has been revealed through past exploration missions is hellishly hot, devoid of oceans, apparently lacking plate tectonics, and bathed in a thick, reactive atmosphere. A less Earth-like environment is hard to imagine. How, why and when did Earth’s and Venus’s evolutionary paths diverge? These fundamental and unresolved questions drive the need for vigorous new exploration of Venus. The answers are central to understanding Venus in the context of terrestrial planets and their evolutionary processes. More importantly, Venus can provide important clues to understanding our own planet – how it has maintained a habitable environment for so long and how long it can continue to do so. Precisely because it began so like Earth, yet evolved to be so different, Venus is the planet most likely to cast new light on the conditions that determine whether or not a planet evolves habitable environments. Current and future efforts to identify planetary systems beyond our Solar System (e.g., the Kepler mission and the Transiting Exoplanet Survey Satellite) are ultimately aimed at finding Earth-size planets around Sun-size stars. The Venus-Earth comparison will be critical in assessing the likelihood that Earth-size means Earth-like for these discoveries.

The planetary science community, through the Decadal survey (Visions and Voyages for Planetary Science in the Decade 2013-2022, National Research Council, National Academies Press, Washington, DC, 2011), has organized current exploration around the following themes:

• Building new worlds—understanding solar system beginnings;
• Planetary habitats—searching for the requirements for life;
• Workings of solar systems—revealing planetary processes through time.

Within the Decadal Survey, the following goals were identified for inner planets research:

• Understand the origin and diversity of terrestrial planets;
• Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life;
• Understand the processes that control climate on Earth-like planets.
The Venus community, as represented by the Venus Exploration Analysis Group (VEXAG), believes that a vigorous exploration program to understand the divergence of Venus from Earth, and to understand the range of possible configurations of extrasolar planets, should play a key role in addressing these themes. Through an extended period where community input was solicited online and through town hall meetings, we have developed this document describing the Goals, Objectives, and Investigations that we believe are most important to be addressed by future exploration to Venus. NASA’s future exploration of Venus should strive to achieve the three following, nonprioritized Goals:

1. **Understand Venus’ early evolution (including possible habitability), and the evolutionary paths of Earth-sized terrestrial (exo)planets.**
2. **Understand atmospheric dynamics, composition, and climate history on Venus.**
3. **Understand how physical and chemical processes interact to shape the modern surface of Venus.**

The current VEXAG Goals, Objectives, and Investigations are given in Table 1, with explanatory text (including possible implementations) following Table 1. The wording of the Table is terse, designed to make the points directly, and without suggesting specific platform or instrument implementations for achieving the GOI. This was done to provide potential PIs the maximum latitude possible in designing missions and instruments to achieve the science GOI. In the accompanying text, we have tried to expand on the terse text of the Table, and to provide possible implementation paths (in sans-serif font), both with respect to instruments and platforms. The implementation texts are not intended to be prescriptive – they represent a consensus on what may be possible in the next decade, and what might contribute to particular Investigations.

The current VEXAG GOI is based on the previous 2016 version of the GOI (web address), and includes all of the prior Investigations, either explicitly or included in broader Investigations (see Table 2). The current GOI differs from the 2016 version in how the Goals and Observations are structured. The 2016 Goals were ‘stovepiped’ along scientific disciplines: Goal 1 concerned only atmospheres; Goal 2 emphasized only surface and interior processes; Goal 3 concerned the interface between atmosphere and surface. While this is a reasonable way to segment the complex science of Venus as a whole system, the current GOI takes a different approach. In light of the recent discoveries of Venus-like exoplanets, and the interest in using planets in our solar system as analogs for those elsewhere in the galaxy, we restructured the Goal 1 to associate Observations and Investigations that were related to the early history of Venus and to observations that would be relevant to exoplanet observations. Goals 2 and 3 relate, somewhat as was done before, with atmospheric and with surface investigations, but with emphasis on current processes rather than early history. Surface-atmosphere interactions are split between Goals 2 and 3, basically on whether they involve Investigations of the atmosphere or the surface.
<table>
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<tr>
<th>Goal</th>
<th>Objective</th>
<th>Investigations</th>
<th>Priority</th>
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<tr>
<td>A. What were Venus’ initial and early states (including its inventory of volatiles including water), and how, when &amp; why did it evolve as it did?</td>
<td>1. Determine the isotopic ratios and abundances of D/H, noble gases, and other elements in Venus’ atmosphere to constrain its planetary accretion, atmospheric evolution, and the possibility of ancient habitability.</td>
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<td>2. Determine whether Venus shows evidence for abundant silicic (granitic) igneous rocks and/or ancient sedimentary rocks (including carbonates), as markers for abundant liquid water in its past.</td>
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<td>3. Characterize the processes by which the atmosphere of Venus has evolved (gains, losses, &amp; changes) over time, including effects of magnetic fields, and incident ions and electrons.</td>
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<td>4. Determine the structure and thermal state of Venus’ mantle, and the size and physical state of the core to place constraints on its accretion and early differentiation.</td>
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<td>5. Search for remanent magnetism in Venus’ surface rocks, to constrain past tectonic regimes, composition of the core, and to climate regimes related to atmospheric loss processes.</td>
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<td>B. How do Venus’s current state and its evolution (in comparison with those of Earth and other terrestrial planets), inform us about planetary evolution paths in general and possible current states, including those of exoplanets in other stellar environments?</td>
<td>1. Investigate Venus’ unique volcano-tectonic surface features (e.g., coronae, tesserae, rigid block &amp; mobile belts) at improved spatial and topographic resolution, to determine which physical parameters allowed them to develop on Venus, and when in Venus’ geologic history these conditions were present.</td>
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<td>2. Determine the current physical and thermal states of Venus' crust and upper mantle (e.g., mobility, spatial variability) to constrain past processes (e.g., crustal overturn) and for comparison to other planets.</td>
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<td>3. Determine if Venus transitioned over time among multiple tectonic regimes reflecting mantle processes), e.g., mobile, stagnant or episodic lid models, and/or other modes of mantle cooling (e.g., heat pipe, squishy lid), and what physical parameters govern(ed) such global transitions.</td>
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<td>4. Determine Venus’ abundances and distributions of heat-producing and volatile elements (in crust, mantle, core), and how abundances and distributions influence differentiation, crust formation and rheology on Venus and other planets.</td>
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<td>5. Determine the atmospheric properties of Venus that could be observable remotely by current and planned exoplanetary telescopes to constrain whether Venus (and Earth) represent typical or atypical states in planetary evolution.</td>
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<td>A. What processes drive the global atmospheric dynamics of Venus?</td>
<td>1. Characterize the dynamics of Venus' lower atmosphere (below about 75km), including: the nature of the retrograde zonal super-rotation, the magnitude of the meridional circulation, radiative balances, generation of mountain waves, and interactions at Venus' surface that affect the planet's rotation rate.</td>
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<td>2. In Venus' upper atmosphere and thermosphere, determine the role of solar-atmosphere interactions by characterizing global atmospheric dynamics and the space environment, including the effects of the space weather (fields and charged particles) environment.</td>
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<td>3. Determine the role of the modes of mesoscale dynamics in redistributing energy and momentum throughout the four-dimensional Venus atmosphere system.</td>
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<td>B. What processes determine the baseline and variations in Venus atmospheric composition and global and local radiative balance?</td>
<td>1. Characterize Venus' atmospheric radiative balance, and the nature of the physical, chemical, and possible biological interactions among the constituents of the Venus atmosphere, the associated radiative interactions, and the atmospheric dynamics.</td>
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<td>2. Determine the physical characteristics and chemical compositions of aerosols in Venus atmosphere as they vary with elevation, including discrimination of aerosol types/components.</td>
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<td>3. Determine the identity of the unknown shortwave absorber in Venus' upper atmosphere, and the nature and magnitude of its influence on both local and global environments.</td>
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<td>4. Assess Venus' surface-atmosphere chemical interactions by determining the composition of, and chemical gradients in, Venus' atmosphere from the ground surface up to the cloud base, both at selected locations and in global perspective.</td>
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<td>5. Determine the products of volcanic outgassing on Venus, and rates of outgassing to constrain its effects on atmospheric composition.</td>
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<td>Goal</td>
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<td>III. Understand how physical and chemical processes interact to shape the surface of Venus.</td>
<td>A. What geologic processes are currently acting on Venus?</td>
<td>1. Search for current volcanic, tectonic, and sedimentary activity on Venus, including: active deformations; eruptions and thermal anomalies; and sediment deposition and erosion. Compare current levels and rates of activity with evidence of that in the past, and evaluate from them current resurfacing rates.</td>
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<td>2. Determine elemental chemistry, mineralogy, and rock types at localities representative of global geologic units to constrain the compositional diversity and origin of the crust.</td>
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<td>3. Determine the structure and thickness of Venus’ crust, in three dimensions, to constrain lithospheric structure and processes and crustal volume.</td>
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<td>4. Search for structural, geomorphic, and chemical evidence of crustal recycling.</td>
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<td>5. Constrain Venus’ interior (i.e., mantle &amp; core) processes that drive current and recent geologic activity.</td>
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<td>B. What are the ages of Venus’ surfaces?</td>
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<td>1. Constrain Venus’ average surface age, and relative ages of surface units, by evaluating impact cratering rates &amp; distributions, the relationship between impactor properties and crater morphology, and the processes that modify craters and their extended ejecta.</td>
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<td>2. Determine absolute (radiometric) ages for Venus rocks at locations that are key to understanding the planet’s geologic history.</td>
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<td>C. How do Venus’ atmosphere, surface, and interior interact?</td>
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<td>1. Evaluate the mineralogy, oxidation state, and changes in chemistry of Venus’ surface-weathered rock exteriors, (including thicknesses of rock weathering rinds), at localities representative of global geologic units.</td>
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<td>2. Determine the causes and spatial extents of global weathering regimes on Venus.</td>
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<td>3. Characterize the coupling of spin states (angular momentum) among Venus’ core, mantle and crust, and atmosphere, and how this coupling has affected Venus’ evolution.</td>
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</table>
Developing a comprehensive understanding of Venus as a system requires making progress in all three Goal areas. Thus, we did not prioritize the Goals. We have identified a small number of prioritized Objectives within each Goal; for each Objective, we have developed a set of prioritized Investigations designed to provide answers to the questions posed by each. The Objectives and Investigations for each Goal are prioritized according to these criteria:

1. Significance of Investigation's result in the context of critical unknowns (knowledge gaps) about Venus and Venus-like exoplanets.
2. Perception of cost/risk/feasibility of the Investigation in the short to intermediate terms, i.e. 10-15 years.
3. Relative value of an Investigation to achieving a stated Objective.

Criteria 1 and 3 are most obvious for a science-based GOI, yet feasibility is an critical factor both in the credibility of this GOI and in its value toward guiding and justifying spacecraft missions and other modes of studying Venus. In regard of cost, risk, and feasibility, we have consulted both the VEXAG Roadmap and VEXAG Technology Plan teams, see their reports parallel to this one. Investigation that seem unlikely to be achieved with current technology (e.g., those that seem to require returned samples) are not excluded, because new technologies may arise that would turn the unthinkable into the commonplace. However, in accord with criteria 2 above, such investigations are assigned lower priorities.

The GOI team found it impractical to assign numerical ordering to the investigations. Because our GOALS crosscut scientific disciplines, strict numerical prioritization led to impossible questions, like “Is determining the noble gas isotopy of Venus’ atmosphere more or less important than improved spatial resolution SAR of Venus’ surface?” Thus, we agreed to prioritize into categories as follows:

**E – Essential.** Investigations that are necessary and sufficient to achieve the objective, and are likely to be feasible in the short- to medium-terms (< ~15 years).

**I – Important.** Either:

1) Investigations that address many aspects of the objective and provide valuable context for other investigations, and are likely to be feasible in the short- to medium-terms (< ~15 years); or

2) Investigations that are necessary and sufficient to achieve the objective, but are judged unlikely to be feasible in the short- to medium-terms (e.g., < ~10-15 years).

**T – Targeted.** Either:

1) Investigations that address particular aspects of the objective that significantly contribute to our overall understanding of Venus, and are likely to be feasible in the short- to medium-terms (< ~10-15 years); or

2) Investigations that address many aspects of the objective and provide valuable context for other investigations, but are judged unlikely to be feasible in the short- to medium-terms (e.g., < ~10-15 years); or

3) Investigations that are necessary and sufficient to achieve the objective, but are judged unlikely to be feasible except in the very long term (e.g., >20 years).
This categorization is shown graphically in Figure 1. Of course, a fourth category, shown in red in Figure 1, encompasses investigations that are of judged to be of lower scientific priority and of lower feasibility. These investigations are not mentioned directly in this document, but may rise in both priority and feasibility in the future.

Table 1. GOI – provided as a separate file.

Text to Accompany Table 1: the GOI.

This following text blocks include explanations and additional information on each of the Goals, Objectives, and Investigations. They should be taken as augmentations and detail on what the GOI team intends, should the Table prove to be ambiguous. These texts are not meant as prescriptions. Text in serif font (Times New Roman) are explanations and additional material about the G, O, or I. Texts in sans-serif font (Arial) are explanations of possible implementations or of data that would address the Investigations. These are meant as examples of how the Investigation could be addressed; they are not intended as prescriptive. The Team hopes and expects that advances in instrumentation and interpretation will lead to new approaches for each Investigation, and that the new approaches will be more scientifically fruitful and feasible than those currently available.
Goal I – Understand Venus’ early evolution (including possible habitability), and the evolutionary paths of Earth-sized terrestrial (exo)planets.

Objective IA. What were Venus’ initial and early states (including its inventory of volatiles including water), and how, when & why did it evolve as it did?

Need text here

Investigation IA1. Determine the isotopic ratios and abundances of D/H, noble gases and other major elements in the atmosphere to constrain the planetary accretion, atmospheric evolution, and the possibility of ancient habitability. [AT]

Significant clues to Venus’ early history, accretion and differentiation, may be preserved in the isotopic and elemental chemistry of its atmosphere. This investigation has highest priority because of the significance of these measurements, and because Venus’ atmosphere is accessible through spectroscopy and through possible sample return. Foremost among atmospheric constraints is the deuterium/hydrogen ratio, D/H, which is known to be outrageously high, approximately 100 times that on the Earth (with significant uncertainties). The high D/H is interpreted as arising through massive loss of H to space, and so suggests that Venus once had enough hydrogen to form significant bodies of liquid water. If so, it is possible that Venus once hosted habitable environments, and possibly life. However, uncertainty in the D/H value allows several scenarios for early Venus, and it is not known if Venus’ early volatiles were like those of the Earth.

The nature of Venus’ early volatiles, sources and compositions, can be addressed by constraints on other elements in its atmosphere, including N, C, Cl, and the heavy noble gases. The isotopic compositions of these gases will help define the sources of Venus’ volatiles, e.g. cometary versus asteroidal. Xenon is of particular importance, because the terrestrial planets appear to have tapped distinct sources of it; it is also possible that Xe has been depleted from the Venus atmosphere in the same processes that have depleted H compared to D.

This Investigation is most directly addressed by mass spectrometry, placing such an instrument in the Venus atmosphere. The most useful analyses would be from depths in the atmosphere where it is well-mixed, deeper than the turbopause. Mass spectrometers have been deployed on probe and lander spacecraft (like the Pioneer Venus probe, and Venera/VEGA), with varying success. These platforms remain suitable, as would a balloon, for deploying a mass spectrometer.

Investigation IA2. Determine whether Venus shows evidence for abundant silicic (granitic) igneous rocks and/or ancient sedimentary rocks (including carbonates), as markers for abundant liquid water in its past.

The presence or absence of liquid water in Venus’ early history is crucial to understanding Venus’ evolution in comparison to other planets, water-bearing (Earth, Mars) or not (Mercury, the Moon). Although liquid water is not present now, its presence may be inferred
from some rock types that may now be preserved at Venus’ surface. A prime candidate for evidence of liquid water is the presence of abundant granitic crust, as has been inferred but not proven for tesserae terranes. On Earth, the abundant granitic rock of its continents was only possible because water was relatively abundant in the crust and mantle where magmas were being generated. Similarly, liquid water may leave its mark in the form of chemical sediments, like carbonate rocks, which might be anticipated in regard of Venus’ CO₂-rich atmosphere. Even clastic sediments can bear the unmistakable large-scale physical signatures of liquid water, as in the sediments of Gale crater on Mars.

These questions can be addressed in part via remote sensing (orbit or balloon), and in part by landed elements. It has been shown recently that basaltic and granitic rocks may be differentiated by their emitted light in the near-infrared, which can be accessed from orbit or from balloon through several spectral ‘windows’ (near 1 µm) in Venus’ thick atmosphere. Basalt would have high emissivity in these wavelengths (being dark in reflectance), and many granitic rocks would have lower emissivities (being light-colored in reflectance). Similarly, sediments rich in silica, plagioclase (as in Gale Crater) or carbonate, which are generally of high reflectance would have low emissivities and be distinct from orbit. The physical characteristics of clastic sedimentary systems may be discernable from orbital or balloon radar, given high-enough spatial resolution. For example, orbital images of Mars show several riverine delta complexes, which certainly imply liquid water.

However, these remote sensing data cannot provide unique determinations of rock type, or of high-resolution physical inter-relationships. Such data can only be acquired by landers, with high-resolution imagers and chemical analysis instruments (such as x-ray fluorescence, gamma ray spectrometry, or LIBS).

Investigation IA3. Characterize the processes by which the atmosphere of Venus has evolved (gains, losses, & changes) over time, including effects of magnetic fields, and incident ions and electrons.

The evolution of the atmosphere of Venus stands in stark contrast to Earth’s other planetary neighbor, Mars. While the surface pressure of Mars’ current atmosphere is a sparse 0.006 bars, Venus hosts a dense 93 bar atmosphere. While Mars clearly speaks to a long history of atmospheric loss, Venus’ story is more complex. Venus simultaneously records a history of loss and extreme replenishment processes. For instance, the high D/H ratio, 150 times that of Earth’s oceans, implies that Venus lost most of its water to space, and recent studies show that O is also lost to space. Yet volcanic outgassing over time, in the absence of clear mechanisms that would recycle volatiles back into its mantle (e.g, no plate tectonics) have created the extreme atmospheric pressure Venus is famous for today. Earth would likely have a similar atmospheric composition to Venus if its crustal and mantle CO₂ and N₂ were released to the atmosphere; thus, Venus’ atmosphere could represent a general end state of a long planetary degassing history. However, Venus and Earth could have started with different initial inventories of carbon and nitrogen. Understanding how the current state of Venus’ atmosphere came to be is crucial for evaluating the processes that may operate to shape the atmospheric compositions of worlds beyond the solar system that may have experienced similar histories to Venus.

Atmospheric loss processes on Venus are, and have been, critically important to the evolution of its atmosphere. In the absence of a strong internal magnetic field, Venus’ upper atmosphere is open to a range of solar effects and loss processes. Venus’ induced field does
afford some protection, but it also transfers momentum from the solar wind to the ionosphere resulting in atmospheric loss. All atmospheres suffer neutral and ionic escape. However, the degree to which this process occurs and the conditions that drive escape depend on the characteristic of not just the planet but the space weather environment in which the planet is embedded. Venus' escape velocity is 10.4 km/s which, unlike Mars, is too great for atmospheric escape to be driven by thermal or photochemical processes. Therefore, non-thermal escape driven by the solar wind is the most important process in the loss of Venus' atmosphere. As such, the study of the solar wind and how it interacts with the Venusian upper atmosphere, both during solar minimum and solar maximum, are imperative in understanding Venus' atmospheric escape and evolution.

Intense solar wind changes such as those generated by co-rating interaction regions (CIRs) and interplanetary coronal mass ejections (ICMEs) are known to increase atmospheric escape. These types of space weather events are capable of producing dramatic increases in solar wind densities, dynamic pressures, magnetic field strengths, as well as generate shocks and accelerate solar energetic particles (SEPs). Studies of ion outflow show that while the escape rate increases by a factor of 2-10, the escape flux can increase by orders of magnitude, especially during ICME events. As Venus only has an induced magnetic field, the increased solar wind dynamic pressure allows the solar wind to penetrate deeper into the ionosphere, causing more intense atmospheric erosion. Additionally, changes in the interplanetary magnetic field which are associated with CIRs lead to magnetic reconnection on the Venusian dayside, also driving atmospheric loss.

Characterization of current atmospheric loss processes has been addressed by the Venus Express orbiter (instruments ASPERA, MAG). For instance, the MAG instrument made the first ever measurements of atmospheric loss of the planet’s day side, and ASPERA has shown that oxygen and hydrogen are lost from the Venusian night side. Better quantification of these loss rates will help us to improve our understanding of the initial inventory of key gases like water vapor. The needs here are for better understanding of Venus’ magnetic field (including reconnection) under a range of solar conditions, better analyses of ion and neutral fluxes (incoming from the sun and outgoing from the atmosphere), and the modes of energy transfer from incoming solar radiation and particles to form hot ions. Better quantification of these loss rates will help us to improve our understanding of the initial inventory of key gases like water vapor. MAVEN-like orbiters at Venus could provide most of this data, and are obviously at high TRL. The magnetic measurements that would be part of such a mission could also be used as part of a study that electromagnetically probed the Venus iron core.

**Investigation IA4.** Determine the structure and thermal state of Venus’ mantle, and the size and physical state of the core to place constraints on its accretion and early differentiation. (Note: This investigation focuses on the ancient state of Venus’ interior, while **Investigation IIIA3** focuses on current and recent activity.)

The deep interior of Venus records processes that occurred in distant times, even as volcanism and tectonics erase ancient features from the surface. Two basic measurements are missing for Venus: total moment of inertia, and radius of the core. The relative sizes of the core and mantle constrain their compositions and the thermodynamic conditions of accretion and differentiation through the abundance of light elements in the core. Magma ocean crystallization
may have produced structures in the lower mantle resembling large low-shear-velocity provinces on Earth. A thick (~1,000 km) layer of recycled basalt above the core/mantle boundary is a unique signature of long-term evolution in the episodic-lid regime of mantle convection—both mobile- or stagnant-lid convection create a much thinner basalt layer in numerical simulations. Related techniques include magnetics, ground-penetrating radar, electromagnetics, gravity, and rotational dynamics.

Determining whether the core is partially or entirely liquid today would strongly constrain thermal models. Energy from giant impacts (kinetic) or rapid accretion (gravitational) may melt the entire core. The conventional view that the mantle cools slowly (or even heats up over time) in the absence of plate tectonics implies that the core would not solidify over the age of the solar system. Indeed, Magellan-era analyses of the tidal Love number implied that the core is at least partially liquid now. However, recent studies with viscoelasticity in the mantle suggest that the current uncertainties in the Love number are too large to rule out a completely solid core. Venus is also the only major planet without evidence for a magnetic dynamo now or in the past. Simulations predict that a liquid, chemically homogenous core would host a dynamo until recent times—plausibly within the surface age.

Data needed for this investigation could include long-term measurements of Venus’ spin rate, precise spacecraft tracking to retrieve tidal Love numbers, precise magnetic field measurements, a long-term seismic network, and analyses of siderophile element abundances in primitive basalts. Spacecraft tracking would be achievable now using standard methods, and to better precision that was possible for Magellan. Measurement of spin rate is also possible now, using standard methods. In fact, recent data from the Venus Express spacecraft suggest that Venus’s spin rate varies over time. Attempts to detect and measure a global magnetic field, at greater sensitivity than in the past, are also possible now, and could be done either from orbit or perhaps from a balloon system. Crustal remanant magnetism could also imply that Venus’ core was vigorously convecting fluid in its recent past.

A global seismic network is, however, a distant goal. There is progress in high-temperature electronics, power systems, and motion sensors, but a working realization of them is likely decades in the future. One technique in development is of detecting seismic activity in Venus’ atmosphere, which is enabled by its high atmospheric density and hence strong coupling to surface motions. It remains to be seen if atmospheric measurements can differentiate seismic signals from those generated in the atmosphere. The lower temperatures at high elevations may also enable future seismometer installation.

Analyses for siderophile elements (e.g., Ni, Co, Os, Re, etc.) in primitive basalts could constrain the type(s) of material from which Venus accreted, the size of its core, and the oxidation state of the planet when the core formed. Some such analyses (Ni, Co, Fe) could now be done on a landed platform; analyses for more highly siderophile elements would require significant technological advances or sample return. Recent sample returns from asteroids have shown remarkable results from very small samples.

**Investigation IA5.** Search for remanent magnetism in Venus’ surface rocks, to constrain past tectonic regimes, composition of the core, and climate regimes related to atmospheric loss processes.
Even if Venus now has no detectable global magnetic field, it might have had one in the past, and traces of that ancient field would be trapped in contemporaneous igneous and sedimentary deposits—partially analogous to the magnetic ‘stripes’ preserved in the Earth’s seafloor, and the remanent magnetic patterns on Mars. Venus has the longest rotational period of the major planets, but is still rotating fast enough to potentially host a dynamo. In particular, the Rossby number in the core of Venus is small enough that the Coriolis force has a large effect on the flow. Despite Venus’ high surface temperature, remanent magnetism could be preserved in the minerals magnetite and hematite, because their Curie temperatures are far higher (585°C and 680°C respectively). Any detection of crustal remanent magnetism would prove that Venus, like Earth, accreted under high-energy conditions that melted and homogenized its core. Furthermore, crustal remanence would indicate that the core once cooled fast enough to convect and that the surface was not much hotter in the recent past.

Detection of a remanant magnetic field, and distinguishing its magnetic components from a (possible) global field and from solar-induced fields would require high-sensitivity magnetometers. It is not clear that measurements from orbit would allow a remanent field to be distinguished from solar-related fields, so landed or balloon platforms seem preferable. The remanent fields are expected to be relatively weak, which would favor a landed platform. However, a balloon platform would give measurements over a range of terrain types and ages, and thereby allow better differentiation of global from remanent fields, but would average over an area approximately the square of the altitude. A high altitude landing could deposit a magnetometer designed to work at high temperatures using technology already available on Earth or readily adapted.

Objective IB. How do Venus’s current state and its evolution (in comparison with those of Earth and other terrestrial planets), inform us about planetary evolution paths in general and possible current states, including those of exoplanets in other stellar environments?

A major focus of astrobiology is the search for habitable conditions and life beyond Earth. We have scrutinized Earth intensely to understand how we might search for habitable conditions elsewhere. In many ways, Venus is the most Earth-like planet in the solar system with its similar mass, radius, and bulk density. Indeed, it is likely that Venus and Earth had very similar starting conditions in terms of their relative compositions of both volatiles and refractory compounds. Yet Earth has been habitable since at least the start of the Archean eon and possibly during the Hadean eon, while Venus’ timescale for habitability is much more uncertain. At some point, the evolution of these two planets diverged dramatically, and Venus is now one of the most uninhabitable planets we might imagine.

In the same way that we can study Earth’s history to understand of how biospheres may evolve over time and co-evolve with their environments, Venus can teach us about an equally fundamental process: how planets reach the end-state of planetary habitability. While Earth shows how self-regulating negative feedbacks (e.g. the carbonate-silicate cycle) work to maintain and preserve habitability on geological timescales, Venus offers us an example of a world whose self-regulation mechanisms failed catastrophically. Without Venus in our solar system, we would be dramatically more inclined to consider the size and mass of the Earth as a fundamental aspect of driving habitable conditions in terms of both the geological and
atmospheric evolution. Yet Venus shows us that knowing the size and mass of an exoplanet is not only insufficient for quantifying habitability, but it demonstrates that a similar planetary structure to the Earth can produce an environment that may be considered at the opposite end of the habitability scale. Therefore, in our searches for worlds circling distant stars, an incomplete understanding of the evolution of Venus and the processes that govern its atmosphere and interior today will hinder our ability to interpret observations of hot terrestrial exoplanets, and will also hinder our ability to understand processes that govern planetary habitability more generally.

**Investigation IB1.** Investigate Venus’ unique volcano-tectonic surface features (e.g., coronae, tesserae, rigid block & mobile belts) at improved spatial and topographic resolution, to determine which physical parameters allowed them to develop on Venus, and when in Venus’ geologic history these conditions were present.

Many key aspects of the surface geologic record are simply unobservable in current imaging and topography data sets. Existing radar maps of Venus have resolutions of hundreds of meters; global altimetry provides topography with a horizontal resolution of worse than ten kilometers. In general, our datasets for Venus have the same quality as those obtained from Mars in the 1970s. Improving spatial resolutions by one or more orders-of-magnitude in global maps would enable delineating individual lava flows, mapping individual fault blocks, and characterizing geologic contacts between volcanic and structural units—fundamentally transforming our understanding of volcanic and tectonic processes on Venus. Timings and sizes of volcanic flows determines whether volatiles were released gradually or catastrophically from the interior.

The measurements that serve Investigation IB1 are radar-related – no other technique can provide global and regional information about Venus’ surface at the required length and height scales. For global coverage, orbital assets are required, and suitable radar orbiters have been proposed several times over the last decade. The orbital radar must operate in SAR mode to provide the requisite spatial resolution, and perhaps at shorter wavelengths than Magellan. It would also be important to transmit and receive circular polarizations, as is done so effectively by Aricebo and other planetary radars.

Radar could also be very effective from a balloon platform – being much closer to Venus’ surface and thus with higher spatial resolution. In addition to SAR mode, it might be possible to utilize “Side Looking Airborne Radar” (SLAR) modes from a balloon.

**Investigation IB2.** Determine the current physical and thermal states of Venus' crust and upper mantle (e.g., mobility, spatial variability) to constrain past processes (e.g., crustal overturn) and for comparison to other planets.

This Investigation is closely related to Investigations IB3, IIA4, and IIA5, in that they all seek to understand properties of Venus’ crust and upper mantle. Although the Investigations are similar, the Goals to which they are applied are distinct. Here, the goal is to constrain the early history of Venus’ crust and upper mantle, based on what is now observable, for itself and to help understand the possible ranges of planetary histories.
Data to address this Investigation would come from indirect and direct geological and geophysical measurements. A high-resolution gravity field, such as might be obtained with a GRAIL-like orbiter mission, would provide crucial information about Venus’ crust and upper mantle. Models of physical and thermal states would be tested against the observed gravity signature (necessarily augmented by high-resolution altimetry data). The thermal states of Venus’ interior can be inferred (to some extent) from gravity-derived densities, but would also be inferred from maps/distributions of surface temperature. Surface temperatures can be inferred from measurement of electromagnetic emission (Planck emission) and estimates of emissivities. Emission and emissivity in the near-infrared may provide better information on surface temperatures than did radar, and it may be possible to detect thermal anomalies which would have their roots in crustal and upper mantle processes.

Direct measurements of Venus’ interior structure might include ground-penetrating radar and seismology. GPR could, in theory, be used to detect contrasts in electrical properties in the subsurface, as has been done for Earth and Mars. It is not clear how deep GPR could be used for Venus – that will depend on laboratory experiments on the electrical properties of Venus-analog materials at appropriate physical conditions. GPR could be implemented from orbit, from an aerial asset, or from a landed platform. Perhaps the most useful GPR would be from a mobile landed asset, but that is nowhere near technical feasibility.

Seismic measurements, tracking body and surface waves from Venus quakes, could in theory provide detailed maps of contrasts in strength inside Venus. A seismic network, with or without active sources, is a distant goal. A promising technique in development is of detecting seismic activity in Venus’ atmosphere, which is enabled by its high atmospheric density and hence strong coupling to surface motions.

**Investigation IB3.** Determine if Venus transitioned over time among multiple tectonic regimes reflecting mantle processes), e.g., mobile, stagnant or episodic lid models, and/or other modes of mantle cooling (e.g., heat pipe, squishy lid), and what physical parameters govern(ed) such global transitions.

*Explanatory Paragraph.
*Observables Paragraph.

**Investigation IB4.** Determine Venus’ abundances and distributions of heat-producing and volatile (not atmophile) elements in Venus’ crust and interior, and constrain their abundances in the whole planet; and how abundances and distributions influence differentiation, crust formation and rheology on Venus and other planets.

Abundances of heat-producing elements (K, U, Th) in Venus are key to understanding the planet’s heat budget and differentiation history. The behavior of a planet’s mantle depends strongly on how much heat is produced in the planet, and where it is produced. For example, if the heat-producing elements are concentrated strongly in the crust (i.e., perhaps granitic crust), then little is left in the mantle to power its convection. Knowing surface abundances of these elements is a crucial precursor datum to understanding measurements of heat flow. And
variations in element abundance ratios like K/Th & U/Th can point to chemical fractionations involving liquid water.

Abundances of ‘volatile’ elements (like Na, K, S, Rb) would provide constraints on the bulk composition of Venus – how similar its composition is to that of the Earth, and thus provide a crucial background to understanding why Venus and Earth are now so different and how the mantle convects.

Barring significant technological breakthroughs, these elemental abundances can only be determined from landed assets. Venus’ atmosphere is too thick for orbital remote sensing of gamma ray emission (as in the MRO GRS instrument) or X-ray emissions. On a lander mission, abundances of heat-producing elements and some volatile elements might be detected by their emitted or induced gamma rays (as did the Venera and VEGA spacecraft); K is likely abundant enough, as are many of the ‘volatile’ elements, to be detected in x-ray fluorescence or LIBS analyses. A determination of surface heat flow would be useful here, but primarily in the contexts of: measured abundances of K, Th, and U at the Venus surface; constraints on the thickness of that surface layer; and constraints on Venus’ bulk abundances of K, Th, and U.

Investigation IB5. Determine the atmospheric properties of Venus that could be observable remotely by current and planned exoplanetary telescopes to constrain whether Venus (and Earth) represent typical or atypical states in planetary evolution.

When we work to understand the basic properties of exoplanets, we must have a robust understanding of our local planetary neighborhood to guide us. For example, comparisons between Earth and solar compositions are being used to predict the interiors of exoplanets based on the stellar abundances of the host star. Such inferences of planetary abundances will benefit enormously from a more detailed understanding of those abundances present within the terrestrial planets of our solar system. Moreover, Venus-like exoplanets may be one of the most common types of terrestrial worlds, and our current and near-future detection and characterization techniques are biased towards detecting exo-Venus analogs over exo-Earth analogs.

The prevalence of Venus analogs will become increasingly relevant in the era of forthcoming exoplanet missions. The Transiting Exoplanet Survey Satellite (TESS) is expected to detect hundreds of terrestrial planets orbiting bright host stars, many of which will lie within their stars’ Venus (runaway greenhouse) Zone. The PLAnetary Transits and Oscillations of stars (PLATO) mission will add further to the inventory of candidate Venus analogs orbiting bright stars and potentially extend to longer orbital period sensitivity than TESS. These new discoveries will provide key opportunities for transmission spectroscopy follow-up observations using the James Webb Space Telescope (JWST), among other facilities, such as the Atmospheric Remote-sensing Exoplanet Large-survey (ARIEL) mission. Observations capable of identifying key atmospheric abundances for terrestrial planets will face the challenge of distinguishing between possible Venus and Earth-like surface conditions and also understanding the data to correctly understand the planetary environment. Discerning the actual occurrence of Venus analogs will help us to decode why the atmosphere of Venus so radically diverged from its sister planet, Earth, and will help to constrain how frequently these processes occur.
Observations of exoplanet Venus-analogs will be aided by measurements of Venus atmospheric D/H ratios and noble gases (which point to evolutionary processes that may also occur on exoplanets; Investigation I1A), observations of atmospheric loss processes that may occur to a more extreme degree on exo-Venus planets, and better constraints on Venusian catalytic photochemistry that affects atmospheric composition.

**Goal II – Understand atmospheric dynamics, composition, and climate history on Venus.**

The study of a planetary atmosphere is essentially the characterization of a planet-scale four-dimensional heat engine. Energy deposition depends strongly on the stellar (solar) inputs and the planetary response to those inputs. The amount of energy absorbed as a function of altitude, latitude, and solar time, and the efficiency with which that energy is distributed throughout the planet are key factors in determining the habitability of a planet. Collection of sufficient data to answer the key questions of atmospheric dynamics and evolution requires a fleet of in situ and orbital platforms capable of building the complete four-dimensional picture. The case of Earth is a good example, exhibiting thousands of ground stations, hundreds of semidiurnal radiosonde atmospheric profiles, and dozens of satellites dedicated to measuring key parameters and providing global context. In order to pursue these same questions in an extraterrestrial sense (for example, the planet Venus), it is helpful to break them down into semi-independent regional questions. The ultimate goal remains to understand how all of the various processes are interconnected, and what is the primary driver of an atmosphere such as that of Venus, and how it came to be.

**Objective IIA. What processes drive the global atmospheric dynamics of Venus?**

Perhaps the most obvious physical characteristics of Venus to an outside observer are its global cloud cover and the atmosphere’s retrograde zonal super-rotation (RZS). Current understanding is that the winds on Venus flow primarily from east to west at almost all altitudes below about 85 km. Near the surface, the wind speed is a truly pedestrian few m/s; but the high density of the 92-bar surface pressure means that these slow winds exert a dynamic pressure that is equivalent to those exerted by a Gale force wind at the surface of the Earth. The wind speeds increase with altitude, reaching a peak in angular momentum at an altitude of about 20 km, and a peak in magnitude at an altitude of around 75 km, just above the cloud tops. Above this altitude, in a region sometimes called the “ignorosphere,” due to the difficulties involved in studying it, the winds transition to a subsolar to antisolar (SSAS) flow, before transitioning back to a zonal super-rotation in the upper thermosphere.

A global-scale wave observed by Akatsuki’s Longwave Infrared camera is tied to the surface topography, and exhibits regular time-of-day recurrence. This has demonstrated the importance of surface-atmosphere interactions at Venus, and the role of solar-atmosphere interactions, even in the deep atmosphere [II.A.1]. This same type of stationary wave feature has been observed in 1980s VEGA Venus Balloon observations: upward-traveling waves perturbed balloon motions at 50-55 km, and stationary waves above highland surface features have been observed in Venus Express data. Furthermore, the coupling of this near-surface phenomenon to
observed behavior near the cloud tops indicates the significance of modulation of vertical propagation of energy and momentum via convection and wave activity [II.A.3]. On Earth, gravity waves can be generated in the troposphere when wind flows over mountainous regions. On Venus, the propagation of such highland waves to the cloud tops may be difficult as convection between the cloud top and ground can disturb wave features, suggesting complex dynamics of the Venus atmosphere. Recent analysis of airglow variability seen in Venus Express data demonstrates that aeronomy and solar-atmosphere interactions play a significant role in driving the dynamics of the upper atmosphere of Venus [II.A.2].

Is the super-rotation driven primarily from above or from below? More likely, it is a combination of both. What is the magnitude of the surface-atmosphere interaction on the Venus atmospheric super-rotation; and what effect does this have on the solid body rotation [III.C.3]? To what extent do thermal tides and solar-atmospheric interactions that drive the SSAS flow contribute to or counter the atmospheric super-rotation [II.A.3]? How effective are the vertical propagation of energy and momentum via waves at a variety of scales, and via convective processes [II.A.3]? In order to answer these questions about Venus atmospheric dynamics, an accumulation of data covering a wide range of altitudes, latitudes, local solar time, geographical area, and with good temporal coverage, both in resolution and duration, are required.

**Investigation IIA1.** Characterize the dynamics of Venus’ lower atmosphere (below about 70 km), including: the nature of the retrograde zonal super-rotation, the magnitude of the meridional circulation, radiative balances, generation of mountain waves, and interactions at Venus’ surface that affect the planet’s rotation rate.

The super-rotation of Venus’ atmosphere has been known from cloud top observations since the early 20th Century. Venus lacks a significant contribution from latent heating resulting from cloud formation, and for which Coriolis forces have less of a restriction on equator to pole energy transport. Despite this apparent simplicity compared to Earth, a full understanding of its structure in the Venus atmosphere and mechanisms for its maintenance remains unresolved. Furthermore, variability in the form of zonal jets has been inferred from Akatsuki observations. Global-scale waves observed by Akatsuki’s Longwave Infrared camera are tied to surface topography (i.e. the crests of major mountain masses), and recur regularly at similar times-of-day. These mountain waves demonstrate the importance of surface-atmosphere interactions for the dynamics of Venus and its atmosphere; generation and dissipation of the mountain waves has been inferred to produce measurable changes in the rotation rate of the solid planet, and to affect solar-atmosphere interactions even in the deep atmosphere [II.A.1]. Finally, models of exoplanetary atmospheres appear to predict even more exotic atmospheric dynamics regimes than is seen at Venus. Solving the problem of Venus’ super-rotation (origin and maintenance) will be an important advance in atmospheric sciences in general, and lend credence to the modelling of exoplanetary atmospheres.

This investigation is focused on characterizing the current state of the deep atmosphere of Venus, semi-arbitrarily defined here as that portion of the atmosphere lying beneath the cloud tops around about 70 km. The reason for this is both theoretical and practical. At this altitude, the zonal wind speed reaches a maximum, before
beginning to transition to the Subsolar-Antisolar flow. This altitude also exhibits a minimum in the vertical temperature profile. Each of these observations suggest a significant transition occurring at or near these altitudes. In a practical sense, 70 km represents an altitude above which it is difficult to obtain long-term and repeated measurement of atmospheric properties from an in situ platform. Above this altitude, the primary means of data acquisition must likely come from an orbital platform; while below this altitude, capability of measurement is expected to be possible from both in situ and remote means.

**Investigation IIA2.** In Venus’ upper atmosphere and thermosphere, determine the role of solar-atmosphere interactions by characterizing global atmospheric dynamics and the space environment, including the effects of the space weather (fields and charged particles) environment.

The Venusian thermosphere experiences strong circulation driven patterns, and gases at these altitudes can be ionized and excited by solar radiation and experience recombination and relaxation back to the ground state on the nightside of the planet. For example, photolyzed CO₂ can generate excited oxygen (Δg) on the Venus dayside, which can circulate to the nightside and downwell to lower altitudes, releasing photons at 1.27 µm as it relaxes from the excited state. Measurements of 1.27 µm oxygen radiation shows significant spatial variability, and bright spots can vanish completely within a single Earth day. Despite these observations of oxygen airglow, ground-state oxygen has never been observed on Venus, implying rapid removal from the atmosphere, possibly through catalytic chlorine chemistry. However, the exact processes driving this remain unknown. In addition, transient green auroral processes have been observed on Venus correlated to solar flares that direct charged particles at Venus. Unlike on planets with magnetic field, whose auroral emissions are concentrated around the magnetic poles, Venusian auroral emissions occur planet-wide.

A recent unexpected surprise is that there is an ambipolar electric field surrounding Venus that is five times as strong as the field in Earth’s ionosphere. This may be attributed to the fact that Venus is closer to the sun and thus receives more solar ionizing radiation, but the details of this process are uncertain. This electric field may be strong enough to strip even heavy O⁺ ions to space, and so better understanding it may be critical for improving our understanding of current and past upper atmosphere loss processes.

Measurements are needed of auroral and other excited gas emissions driven by solar processes to understand the causes and variability of these events. These observations could be accomplished through remote observations such as through an orbiter. Observations at different spatial scales will allow investigations of small-scale and planet-scale processes. Measurements of the ionospheric potential drop in the Venusian atmosphere as have been done on Mars will help to constrain electric field properties. Furthermore, observations of superthermal photoelectrons and other outflows of ions and electrons on Venus may place better constraints on loss processes occurring due to the Venusian ambipolar electric field.
Investigation IIA3. Determine the role of the modes of mesoscale dynamics in redistributing energy and momentum throughout the four-dimensional Venus atmosphere system.

While the previous two investigations segregated global scale processes and observations according to vertical spatial domain (above and below an approximate altitude of 70 km, and the dominant processes in each), this investigation focuses on the smaller spatial scale processes and observations that can, taken as a whole, drive planetary atmosphere dynamics on either local or global scales. In a modelling sense, these processes would often be termed “sub-grid-scale” processes. In order to adequately model a planetary atmosphere, these processes must be sufficiently understood so as to be reliably parameterized in a general circulation model.

These processes, including the behavior and evolution of convective cells, horizontal and vertical wave propagation, and other mesoscale structures, can be of small enough scale, whether spatially or temporally, to be an impractical target for an investigation focused on characterizing global scale processes. Nevertheless, such features and processes can be observed from orbit, as demonstrated by the discovery of numerous mesoscale features in both Venus Express and Akatsuki data. Direct in situ measurement of the local dynamics of isolated convective structures and/or wave propagation would also contribute to this investigation, though, without global or regional contextual information, spatio-temporal degeneracies will remain, as they have for the interpretation of the VeGa balloon meteorological data.

Objective IIB. What processes determine the baseline and variations in Venus atmospheric composition and global and local radiative balance?

The atmosphere of Venus is a highly coupled chemical, radiative, and dynamical system. The composition and evolution of the atmospheric constituents are strongly regulated by chemical processes in the highly complicated, sulfur-based chemistry atmosphere. Yet, significant questions remain regarding the identities and/or the sources and sinks for many of these constituents.

A proxy for the atmospheric dynamics of Venus is the rate and global distribution of lightning. Lightning has been mapped on the night side at middle and low latitudes by Pioneer Venus and at polar latitudes by Venus Express. More recent ongoing observations by the Lightning and Airglow Camera on Akatsuki promise to provide statistical assessments of the presence of lightning in the Venus atmosphere. NO abundance in the Venus atmosphere suggests that lightning occurrence could be greater on Venus than on Earth [II.B.1].

The surface of Venus is an inhospitable 735K, with a mean surface pressure of about 92 bars. This is a result of – despite the global cloud cover reflecting away about 75% of the incident solar flux – the significant warming caused by the greenhouse effect, caused primarily by the atmosphere’s CO₂ and H₂O. However, despite such hostile surface conditions, Venus also hosts one of the more favorable abodes for life in the solar system, in its clouds, where temperatures and pressures are considerably more Earth-like [II.B.1].

A hypothesis that has regained traction lately suggests that the unknown absorber in the Venus atmosphere could be the result of biological processes. The similarity of the absorption profile to that of certain thermophilic and acidophilic organisms on Earth, combined with the relatively benign environment, replete with access to a sulfuro-hydrological cycle capable of...
supporting aqueous chemistry and resource exchange, lends newfound credence to this idea [II.B.1]. On the other hand, there is a competing claim that the inorganic abiotic molecule OSSO and its isomers are the ‘unknown absorbers.’

Of the 25% of incident solar flux that is not reflected away by the clouds, approximately half is absorbed in the vicinity of the clouds, making Venus unique among the terrestrial planets in that the atmosphere is heated primarily from above, rather than from below [II.B.1]. Most of this radiation is absorbed by SO\textsubscript{2} and a species whose existence has been known for decades, but whose identity remains a mystery. SO\textsubscript{2} has been shown to exhibit significant variability on timescales ranging from days to decades, with modelling suggesting variability on geological timescales as well [II.B.4,5].

**Investigation IIB1.** Characterize Venus’ atmospheric radiative balance, and the nature of the physical, chemical, and possible biological interactions among the constituents of the Venus atmosphere, the associated radiative interactions, and the atmospheric dynamics.

- **Explanatory Paragraph.**
- **Observables Paragraph.**

**Investigation IIB2.** Determine the physical characteristics and chemical compositions of aerosols in Venus atmosphere as they vary with elevation, including discrimination of aerosol types/components.

The Venusian aerosols have a major impact on the Venus greenhouse effect and its remotely observable properties. While the primary constituent of the upper clouds has long been known to be spherical particles of highly concentrated sulfuric acid with typical radii of one micron, the exact nature of the Venusian aerosols is incompletely known. A submicron mode of particles is known to exist in both the upper clouds, as well as in and below the middle and lower clouds. However, the size distribution of this smallest mode of particles at all altitudes remains somewhat underconstrained by the available data. Furthermore, in the upper clouds, the composition has been assumed to be sulfuric acid, but this has never been definitively shown. In and below the lower and middle clouds, their composition remains similarly unknown. Finally, the largest mode of particles, the Mode 3 particles found in the middle and lower clouds, remains a controversial topic. The night side near infrared inhomogeneities are attributed largely to variations in the Mode 3 population, yet their existence remains unconfirmed and their composition unknown [II.B.5]. It has been suggested that Mode 3 particles may have a crystalline component, or that they represent the tail end of the distribution of large Mode 2 particles.

In-situ nephelometer and mass spectroscopy of cloud aerosols would clear up uncertainties in their size distributions and compositions. Observations would be required at altitudes throughout the cloud column because different populations of aerosol sizes and types occur at different altitudes.

**Investigation IIB3.** Determine the identity of the unknown shortwave absorber in Venus’ upper atmosphere, and the nature and magnitude of its influence on both local and global environments.
Short-wavelength visible and near-ultraviolet light is unaccountably absorbed in Venus’ upper atmosphere. The effects of this unknown absorber are strongest in the near-ultraviolet, but are apparent well into the wavelengths of visible light. The unknown absorber varies in strength over space and over a wide range of timescales. Its importance, besides that of an enduring curiosity, is that it controls much of the deposition of solar insolation into the atmosphere, and thus the thermal structure of the atmosphere. It is possible that the unknown absorber is the molecule OSSO and its isomers, that iron chlorides are important absorbers, or even that the unknown absorber in the Venus atmosphere is a product of biological processes.

Mass spectrometry is the measurement most likely to cleanly address this investigation. The Venus atmosphere would be ingested into the instrument while it moved through the region of the short-wave absorber, and the absorber’s identity would be inferred directly or indirectly by the mass spectrum. The platform most appropriate to carry this mass spectrometer is likely a descent probe, or high-altitude airplane or balloon.


If this (or other similar) claim is verified, Investigation IIIB3 would be deprecated to “…the nature and magnitude of its influence on both local and global environments…” and its priority reduced from I to T.

Investigation IIB4. Assess Venus’ surface-atmosphere chemical interactions by determining the composition of, and chemical gradients in, Venus' atmosphere from the ground surface up to the cloud base, both at selected locations and in global perspective.

Venus’ rock and its atmosphere intersect at the surface, where temperatures of ~470°C and pressures ~90 bars virtually ensure geologically rapid chemical reactions. These reactions will impart significant changes to both atmosphere and surface: effects on the surface are considered in Investigations IIIB3 and IIIB4.

Away from sites of active volcanic outgassing (see IIB2), Venus’ rocky surface should interact chemically with the ambient atmosphere, and affect it in several known or suspected ways. First, the average Venus atmosphere is oxidized compared to basaltic rock, and so surface chemistry should produce reduced gas species, like CO from CO₂, and SO₂ or S from SO₃. Second, SO₃ in the atmosphere is predicted to react with Ca-bearing silicates to form CaSO₄, anhydrite, thus reducing the proportion of atmospheric sulfate. Third, there are suggestions that atmospheric halogens could exchange with the surface, perhaps reducing the Cl/F ratio by formation of Cl-bearing phosphate phases. Fourth, there is strong evidence in equatorial and northern highlands that atmosphere-surface chemistry varies with elevation. And, if Venus’ volcanic rocks include hydroxy-bearing igneous minerals (like amphibole or biotite), their decomposition should release hydrogen (with D/H values of the interior) to the atmosphere.

To determine gradients in atmospheric chemistry on a global scale, to a greater fidelity than is now known, will require detailed spectroscopic observations and
interpretations. Now, the chemistry of the deep atmosphere is known mostly from modeling of high-resolution infrared spectra taken from Earth, specifically modeling the pressure broadening of specific spectral lines of compounds of interest. Acquiring better global spectra will be useful, but especially in the context of continued improvement in modeling the effects of pressure on the specific line widths and strengths. Determining gradients on a regional scale would be enabled by orbital or balloon platforms carrying high-spectral-resolution spectrometers, so that one could apply the pressure effect models to specific locations – e.g., is Venus’ near-surface atmosphere at the equator the same as that over Maxwell Montes. Determining gradients at a local scale would be accomplished best by probe platforms, with suitable mass spectrometers, designed to sample Venus’ lower atmosphere at frequently as the probe descended to the surface. Such measurements could then provide a ‘ground truth’ to help interpret spectra taken from balloon, orbit or Earth.

**Investigation IIB5.** Determine the products of volcanic outgassing on Venus, and rates of outgassing to constrain its effects on atmospheric composition.

Categorizing the amount and type of volcanism through planetary atmosphere measurements can provide a wealth of knowledge about the interiors of terrestrial planets (and exoplanets), including into the type(s) and composition of crust on a planet’s surface (available for weathering and buffering the planet’s atmosphere composition), the abundance of volatiles found in the planetary interior, the dynamics of the planetary interior, and potentially even the first order structure of the planet. Volcanism extreme enough to produce flood-like lavas on terrestrial planets in our Solar System requires either a very young planetary body or one with sustained vigorous convection and/or inefficient heat transport in the planet’s interior. Thus, the changing character of volcanism on planet through time will also provide a means of categorizing a planet’s relative age and/or convective vigor and interior structure.

In our solar system, this changing character of volcanism is perhaps exemplified by Venus. On Venus, transient and high concentrations of SO₂ in the atmosphere and thermal anomalies on the surface have pointed to currently-active volcanism, supported by a host of volcanic surface features and a young cratering-based surface age of 500–800 Ma. Venusian magmatism has resulted in rapid resurfacing in the past, which requires vigorous mantle convection and a high rate of mantle melting, and provides insight into Venus’s mantle composition. The lack of plate tectonics on Venus suggests a conducting lithosphere on top of a convective mantle, where mantle plumes bring heat flow to the base of the lithosphere, from which it is conducted to the surface. This inefficient mode of heat transport may ultimately result in periodic complete overturn of the lithosphere and global resurfacing.

Although it is vitally important to know the composition, volume, and timing of volcanic gassing to the atmosphere, there is no obvious simple path to acquire this information. The global nature of the investigation, though, suggests that global remote sensing platforms are most appropriate. Volcanic eruption locations and rates could be monitored with a VNIR imaging system, such as VIRTIS on Venus Express, which sees the surface through atmospheric windows. The thermal emission of an active volcanic source would far override the thermal emission of the surface at normal temperatures. To determine the composition and mass of volcanic gas, perhaps one could use an orbital spectrometer, like that in IIB4, that could monitor the abundances of selected
species at depths in the atmosphere. With such data, one could in theory monitor the location and size of volcanic plume over time.

**Goal III – Understand how physical and chemical processes interact to shape the modern surface of Venus.**

The current surface of Venus, as best known from Magellan radar data, is far different from those of the Earth, Moon, or Mars; it seems to present a fundamentally different mode of surface geology and thus of processes that shape its surface. Although some Venusian surface features are familiar from Earth, such as shield volcanoes, lava plains, mountain ranges, and impact craters, others are unique to Venus: high-standing, intensely deformed tesserae, quasi-circular volcano-tectonic coronae, and vast, intricate fracture patterns on the plains.

The plate tectonic system that powers most geologic processes on Earth’s surface does not act on Venus (although in some hypotheses, such a system once did); there are no signs its characteristic features: trenches at subduction zone, volcanic arcs, or crustal spreading. The recent tectonics of Venus seems dominated by large rift systems, by ‘jostling’ of crustal blocks, and by regional-scale systems of fractures. In the absence of plate tectonics, particularly crustal spreading (i.e. mid-ocean ridges), is not clear how heat is released from Venus’ interior. A variety of un-Earthly convective models and planetary resurfacing scenarios have been proposed to explain Venus’ tectonics, and only new data can generate breakthroughs in understanding. Has the planet resurfaced primarily through lavas flowing over an immobile crust? Did Venus have an earlier phase of plate tectonics (or more generically, mobile-lid tectonics) that erased previous impact craters and basins? If the planet has never had plate tectonics, how has Venus lost its heat over time? How is it losing its heat now? How have these processes affected the internal differentiation of Venus, particularly the volume and types of crustal rocks? How does tectonics affect habitability?

Volcanism is widespread on Venus, and lava flows cover most of its surface. Most (not all) large volcanoes are associated with rift systems; perhaps more lava has come from fields of small shields or from flooding flows that did not produce central volcanoes. Most unfamiliar are coronae, quasi-circular volcano-tectonic structures, in which intense volcanism seems tied to concentric uplifts and downwarps of the surface. Coronae may be the surface expressions of diapiric uplifts from Venus’ mantle, but other origins are possible. In a few places, the morphology of Venus’s volcanoes suggests very viscous lava, as represent on Earth granitic (rhyolitic) compositions. How might those arise?

Among the extensive lava fields, and partially buried by them, are intensely deformed ‘tesserae’ regions, and the Ishtar Terra highlands, surrounded by mountain ranges. Tesserae are unlike known areas on Earth (or other planets), and their origins are hotly debated. Some evidence suggests that they have silicic chemical compositions, like granite, and so could be analogous to continents or continental crust on Earth. Ishtar Terra, standing at relatively high elevations above basaltic plains, appears at first glance like a continent, ringed by compressional mountains. In particular, the mountains to its east, Maxwell Montes, have been compared to the Earth’s Tibetan plateau, which is granitic (continental) crust uplifted by plate tectonic processes.

Impact craters pock all of these terrain types, but this impact record is particularly puzzling. Magellan radar revealed fewer than a thousand impact structures on Venus; this indicates a young surface age (formally, a crater-retention age) much closer to Earth’s than the other, more heavily cratered inner Solar System bodies. However, the craters are distributed...
quasi-randomly across Venus, even though their target surfaces are not randomly distributed and are clearly of different relative ages.

Venus’ surface has been affected by erosion and ‘weathering,’ although the causes and natures of both are not clear. Wind streaks across Venus’s surface show that some sediment can be transported, although not perhaps at the measured surface wind speeds of meters per second. Recent deposits from impact craters, presumably fragmental ejecta, disappear with time, but it’s not known if this is a physical or chemical process. And the radar properties of Venus’ surface vary widely with elevation, especially near a critical elevation of ~5 km. In the north, around Ishtar Terra, radar backscatter increases abruptly above that elevation; near the equator, on Aphrodite Terra, radar backscatter decreases abruptly above that elevation. The causes and implications of this difference are not clear.

More than any other planet in the Solar System, Venus needs to be viewed as an integrated system, rather than as relatively independent atmosphere, surface, and interior. The high pressure and temperature at Venus’ surface imply that atmosphere-surface chemistry affects both; recent evidence from the Akatsuki orbiter show that surface morphology affects atmospheric physics at least to the top of the cloud layer. Because most of Venus’ surface is covered by lava flows, its surface geology cannot be evaluated independent of the source(s) of those lavas – Venus’ interior, and its tectonic and convection regimes. And Venus’ volcanos apparently do, and presumably did, inject significant quantities of gas into the atmosphere, which would affect its chemistry (and thus of course, the composition and mineralogy of the surface).

**Objective IIIA. What geologic processes are currently acting on Venus?**

The geology of Venus displays much of the tectonic and volcanic elements that on Earth provide evidence for plate tectonics. However, they do not form an interconnected network, and activity has decreased in intensity over the available geological record. Globally consistent trends in the sequence of stratigraphic units emplaced over the last half billion years or so point to an adjustment of the interior to a new stagnant lid convection regime. Whether these changes are globally synchronous, whether any activity is ongoing, and what Venus was like before this transition started, are all fundamental questions that remain to be answered in a satisfactory manner. To address these questions, it is necessary to quantify the activity that may still take place today, and constrain changes in the tectonic and volcanic activity over the available geological records, which spans less than a fifth of the history of Venus. Is there evidence for diversity in the composition of deposits in the surface of Venus? How much of the crust, not just at the surface but also at depth, represents activity that predates the emplacement of the regional plains that today cover the majority of the planet? Is it possible to identify sedimentary deposits, that would potentially collect materials from various locations on the planet? Studying the diversity of geological features today not only helps understanding current activity but also constrains how the planet has changed over the last billion years and possibly earlier.

**Investigation IIIA1. Search for current volcanic, tectonic, and sedimentary activity on Venus, including: active deformations; eruptions and thermal anomalies; and sediment deposition and erosion. Compare current levels and rates**
of activity with evidence of that in the past, and evaluate from them current resurfacing rates.

Venus’s surface shows signs of great geological activities, volcanic, tectonic, and sedimentary, shows a wide range of volcanic and tectonic features, indicative of significant surface modifications within the last billion or so years. Volcanic features include central shield volcanos, shield fields, extensive plains volcanism, and effusive domes. While there have been hints of current volcanic activity (spikes in SO$_{2}$ abundances in the upper atmosphere), there has been no clear evidence of recent volcanic activity, such as new lava flows or thermal anomalies. Our temporal coverage of Venus’ surface is, however, very limited and our data on surface temperatures is similarly limited and of coarse spatial resolution.

Tectonic features on Venus include rifts, mountain belts, folds, strike-slip fault systems, and possibly subduction zones. Many are concentrated in demonstrably older terrains (the tesserae), and along specific rift and convergence zones (Maxwell Montes). Most volcanic plains show some wrinkling deformation, but some young volcanic plains appear to be undeformed. It is not clear, then, if the intensity of deformation has decreased over time, or in intensity over the entire available geological record or if deformation has become more localized. This inspires several questions. Are rift zones currently active? Is the evidence for recent extension balanced by subduction and strike-slip features, producing a sort of proto-plate tectonics regime? Are regions deformed earlier truly inactive or could they be reactivated today? In what way do partially-buried early tectonic features differ from more recent structures?

Venusian sedimentary processes appear minor compared to igneous and tectonic, but available radar evidence does not preclude the presence of widespread porous surface deposits. Clear evidences of sedimentary activity include: dune fields at scattered locations, aligned light or dark streaks (as by wind), fine-grained materials observed at the Venera and VEGA landing sites, and parabolic deposits and streaks downwind from recent impact craters.

Questions of current geological activity are best addressed by time-resolved observations, of which several types are possible. Simplest would be comparison of SAR images of the surface taken at different times, e.g. comparing Magellan images with those of a mission 30 years later. Another approach, with closer time resolution, would be SAR interferometry – computing the quantitative differences in elevation/location between successive passes of a single SAR instrument. The higher spatial resolution from this SAR, the more subtle signs of activity could be detected.

Other investigations can address parts of these questions. Most types of current tectonic activity would produce earthquakes, which then could be monitored by a seismic network on the surface or possibly by detection of seismic waves in the atmosphere. Current and recent volcanic activity could be detectable as temperature (thermal) anomalies, which could be detectable either as regions of anomalously high radar or near-infrared emission.

**Investigation IIIA2.** Determine elemental chemistry, mineralogy, and rock types at localities representative of global geologic units to constrain the compositional diversity and origin of the crust.

It would be ideal to have global data on the elemental and mineralogical composition of the Venus surface, as has been possible for Mars with data from the GRS and CRISM.
instruments, in orbit. With such data, one could determine what the highland units of Venus are made of, what sorts of basalts cover Venus’ plains, whether the product of shield volcanos are different from those of the plains, what radar-bright crater halos are made of, etc. Unfortunately, Venus’ thick atmosphere precludes such a synoptic view of the surface. It is possible to obtain from orbit high-resolution radar images, in which pixel properties can be interpreted to obtain some mineralogical and chemical data. The surface can also be observed from orbit, in low spatial resolution, through some near-IR windows, by which some data on surface mineralogy and/or chemistry can be inferred. Otherwise, detailed data on surface mineralogy and chemistry (which may act as ground-truth for radar and near-IR) must be obtained at the surface. Given the opacity of Venus’ atmosphere, a reasonable compromise is to chose characteristic spots for each type of surface material, and obtain mineralogical and elemental data by means other than traditional remote sensing.

Measurements to satisfy this investigation would be, at least with current technology, limited to those possible in situ with landed platforms. Possible instruments to determine elemental chemistry include: gamma-ray spectrometry (passive and neutron activated), X-ray spectrometry, and LIBS. Instruments to determine mineralogy include: Raman spectrometry, IR reflectance spectrometry, and X-ray diffraction. Determination of rock type, both chemical and textural classifications, would follow directly from these data.

**Investigation IIIA3.** Determine the thickness and structure (in three dimensions) of Venus’ crust, in order to constrain lithospheric structure and processes and crustal volume.

In the absence of evidence for large-scale subduction on Venus over the last half billion years or so, Venus’ crust can be regarded as a semi-permanent record of activity over that time period. In the context of a short-lived and sudden episode of intense activity manifested by near-global resurfacing, the thickness of crust of Venus can tell us how much magmatism took place at that time, and variations related to location of more ancient materials like tessera or more recent units, like rift zones, can provide the means to quantify activity outside of the resurfacing event. Information about the structure of the crust, including the thickness of plain units and the penetration of faults, are also important to reconstructing the history of geological activity on Venus and how it may have changed over time. The lithosphere thickness, probed for example by analyzing patterns of faulting and evidence for elastic flexure, can provide a record of the evolution of the planet even under conditions where magmatism is not present. Linked with chronostratigraphic knowledge, the changes in lithospheric thickness over time inform and constrain the evolution of the interior of the planet and its geodynamic regime.

The structure and thickness of Venus’ crust can be measured, in broad brush, via several approaches. Gravity and altimetry data have provided strong constraints on the thicknesses and distributions of Venus’ crust (in concert, of course, with theoretical investigations and experimental analyses of materials properties). Gravity and altimetry data could be improved significantly by, for instance, a GRAIL-like gravimeter system, and global stereo DEM topography. Shallow crustal structure might be investigated via ground-penetrating radar (based either on an orbiter or on aerial assets).

Seismology is the nominal method for determining crustal structure on the Earth, but that would require a global seismic network which is a distant goal. There is
progress in high-temperature electronics, power systems, and motion sensors, but a working realization of them is likely decades in the future. A promising technique in development is of detecting seismic activity in Venus’ atmosphere, which is enabled by its high atmospheric density and hence strong coupling to surface motions. It remains to be seen in atmospheric measurements can differentiate seismic signals from those generated in the atmosphere.

Investigation IIIA4. Search for structural, geomorphic, and chemical evidence of crustal recycling.

Crustal recycling means (in this context) geological transport of crustal and near-surface materials to depths in a planet where they may participate in magma generation, assimilation, and fractionation. Planetary differentiation tends to bring low-density, volatile-richer, and easily melted material to the planet’s surface (i.e., the crust). The remaining silicate material (the mantle) becomes depleted and refractory, and thus more difficult to melt or deform. If crustal material can be cycled back to depths in the lower crust or mantle, those regions would melt at lower temperatures, and be less viscous and more likely to convect. Exactly this process on Earth (via subduction) permits extensive arc volcanism, and has hydrated the upper mantle to reduce its viscosity in convection. Thus, it is important to know whether Venus’s upper crust and its volatile constituents (e.g., alkali metals, CO\(_2\), SO\(_2\)) are cycled into its interior. Some geomorphic evidence of recycling has been offered, in the forms of putative subduction or underthrusting zones.

Many types of observations could bear on this investigation, but none by itself can necessarily prove the existence or define the importance of crustal recycling on Venus. Geomorphic evidence has suggested the presence of subduction or underthrusting in limited areas – these ideas could be tested with high-spatial-resolution SAR images and altimetry, the latter especially useful when coupled with a high-resolution gravity field. Although suggestive, these data and models based on them may (or may not) indicate that crustal material descends to depths at which ‘recycling’ can occur. Another sort of data would be the chemical compositions of lavas associated with potential recycling zones (e.g., like arc volcanics on Earth). These lavas will bear chemical signatures associated with the recycled material, and could be expected to be (by analogy with Earth arc lavas) enriched in volatile components, and enriched in elements that are soluble in those volatiles. For Venus, recycled water would not be significant so one can look for analogies to the compositions of CO\(_2\)-rich lavas on Earth, like carbonatites. Those are typically enriched in light rare earth elements, phosphorus, and niobium – one might expect similar enrichments in Venus’ lavas affected by crustal recycling.

Investigation IIIA5. Constrain Venus’ interior (i.e., mantle & core) processes that drive current and recent geologic activity.

Most tectonic and volcanic activity is driven by interior processes that allow the planet to transport and lose its internal heat, including heat remaining from early accretion and differentiation, and that produced by decay of radioisotopes. Venus and Earth, with their similar sizes, densities, and positions in the solar system, would be expected to have similar heat budgets. However, their current modes of heat transfer are quite different: Earth’s heat transfers
are dominated by processes of plate tectonics, in which the strong rigid lithosphere is able to break, bend, and be recycled to the interior of the planet, efficiently cooling the deeper mantle. Venus shows no evidence for an equivalent network of plate boundaries, implying a different geodynamic regime. It remains to be explained exactly how Venus loses its internal heat. Is Venus in a stagnant lid regime, where the stress between lithosphere and (moving) asthenosphere is inadequate to break the lithosphere and recycle it? If so, is it a “hot” stagnant lid that may precede plate tectonic episodes, or a “cold” stagnant lid where asthenosphere motion will never be able to break the lithosphere? Or, does Venus operate in an episodic regime, where the lithosphere is usually in a stagnant regime mode, but is punctuated by short-lived episodes of extremely intense activity? Is the geodynamic regime instead one where heat is mostly transferred by magmatic activity, being a “heat-pipe” regime or “intrusive magmatism” regime? Can the systematic changes in tectonic and magmatic activity in the geological record be explained by the transient adjustment to a new interior geodynamic regime? If so, was that transition triggered by a change in surface condition or interior configuration? Is that change permanent or do we expect a return to a more active surface? Can the young age of rift zones be taken as evidence for the onset of plate tectonics on Venus?

Several lines of evidence can be applied to partially address this investigation. The presence and distribution of hot spots (thermal anomalies) on the Venus surface may be distinctive for different mantle tectonic regimes. For instance, a ‘heat pipe’ regime should have few but very hot anomalies. Detecting thermal anomalies could involve comparison of maps high-resolution altimetry with that of thermal emission. High-resolution gravity maps, again combined with altimetry, may define areas of deep density anomalies, some of which would represent thermal anomalies. High-resolution SAR may reveal surface topographic features that can be modeled to infer deep processes. And finally, of course, detection of remanent crustal magnetism would provide an important constraint on the spin and evolution of Venus’ core.

Objective IIIB. What are the ages of Venus’ surfaces?

The ages of surface materials on Venus are poorly known, both relatively and absolutely, and yet are crucial constraints on models for the whole of Venus’ geological history and evolution. Venus’ few impact craters are distributed randomly or semi-randomly across its surface. Does this distribution mean that all of Venus was resurfaced in a short interval and has lain static thereafter? Or is the crater distribution consistent with episodic resurfacing at varying lengthscales? Are all tessera terranes contemporaneous, and interpretable as a global stratigraphic unit? Or is each tessera an independent product of underlying, time-varying processes? Is the apparent crater-count age for Venus’ surface, ~ 1 Gya, a real single age? Answers to all of these questions have huge importance for understanding Venus’ history, geological evolution, and climate evolution.

Investigation IIIB1. Constrain the relative ages of Venus’ surface units and the average age of its surface.
Magellan SAR radar images have permitted development of a framework of relative for surface units on Venus, but better constraints would be important. In one instance, recognition of partially filled impact craters, filled with basalts of Venus’ plains, have helped constrain the nature of the impact record. However, Magellan SAR lacks the spatial resolution to recognize fill in smaller craters, and even to detect smaller craters on rough terrain. In another instance, ejecta from some impact craters is recognizable in SAR, and is inferred to be modified and removed over time. However, the details of that modification and removal are not apparent in Magellan SAR. In Magellan SAR, few details are visible within smooth plains lava units – flow fronts are rarely observed, and they would be important for understanding volume and repetition rates of the effusions.

To address this investigation, one would want surface imaging at much higher spatial resolution, with better control on small elevation changes or slope breaks (e.g., to detect flow fronts), improved signal/noise for flat (i.e., radar-dark) surfaces, and data about the surface materials characteristics (e.g., porosity). These measurements could be obtained with radar systems that are significantly improved over the Magellan data. Improved spatial resolution might come from improved SAR systems, perhaps higher-frequency radar. Improved control on elevations and slope breaks could come from better altimetry and low-depression-angle SAR or SLAR. Improved control on the geography of flat surfaces might be gained by bistatic radar experiments, and better control on materials properties could come from use of circular polarizations. These radar experiments could be hosted by orbital assets (giving global coverage), or by balloon or other aerial assets (giving higher spatial resolution, but only regional coverage).

Investigation IIIB2. Determine absolute (radiometric) ages for Venus rocks at locations that are key to understanding the planet’s geologic history.

The absolute ages of Venus’ surface units are ultimately crucial for understanding the geological and geophysical evolution of the planet. As described under Investigation IIIB1, Venus’ surface is relatively young, but the absolute average age is uncertain from many factors. Knowing the absolute ages of key surface units (e.g., tesserae, coronae, lava plains) would provide quantitative calibrations to the average age of the planet’s surface, to relative ages from unit superposition, and to concepts of global stratigraphic units. Knowing absolute ages would provide a key constraint on global stratigraphy, to geological and geophysical history, and thus to understanding the dynamics of Venus in comparison to Earth and Mars.

Measurement of absolute ages for Venus surface rocks would depend on radioisotope chronometers – analyzing the abundances of parent and daughter isotopes in suitable radiochronometric systems. Suitable chronometers could include the Rb-Sr and Sm-Nd systems (and potentially others), all of which require high-resolution mass spectrometric analyses of relatively rare elements and their isotopes. The K-Ar radiochronometer is not suitable for Venus, as its surface temperature is so high that radiogenic Ar is rapidly lost to the atmosphere.

Mass spectrometry in a landed element on Venus may be possible – spacecraft mass spectrometers designed for Rb-Sr are under development and have been proposed for lunar landers. However, model-independent age determinations require preparation of sample separates with different Rb-Sr ratios – this level of sample preparation and handling has not been demonstrated in a spacecraft setting.
Alternatively, Venus samples could be easily analyzed on Earth with standard instruments, but the technology of Venus sample return is far from mature. Because of these issues, this Investigation is unlikely to be achievable in the coming decade or two.

**Objective IIIC. How do Venus’ atmosphere, surface, and interior interact?**

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**Investigation IIIC1.** Evaluate the mineralogy, oxidation state, and changes in chemistry of Venus’ surface-weathered rock exteriors, (including thicknesses of rock weathering rinds), at localities representative of global geologic units.

Venus’ rock and its atmosphere intersect at the surface, where temperatures of ~470°C and pressures ~90 bars virtually ensure geologically rapid chemical reactions. These reactions will impart significant changes to both atmosphere and surface: effects on the surface are considered in Investigation IIB4.

On one hand, the atmosphere is moderately oxidizing (being mostly CO₂), and the basalt rock of Venus’ volcanoes and plains is reduced. Their reaction should coat the basalt with a weathering rind of oxidized iron minerals (hematite or magnetite). Hematite (Fe₂O₃) is interpreted to be the product at low elevations, based on lander and orbiter VNIR data, and the formation rates of these rinds could provide a way to obtain ages of young volcanic units.

Measurements needed for this investigation would rely primarily on landed assets, as the need for mineralogical and chemical information with depth seem to preclude most remote sensing measurements. Mineralogical data could come (as above) from Raman or near-infrared spectrometry, or X-ray diffraction; chemical data could come (as above) from LIBS, or X-ray fluorescence. Analysis for these at various depths obviously requires a tool for drilling, cutting, or scraping surface material. These analyses would only be fully interpretable when supported by laboratory experiments and theoretical models.

**Investigation IIIC2.** Determine the causes and spatial extents of global weathering regimes on Venus.

There is evidence that Venus’ rock weathering (atmosphere-surface chemistry) varies at hemisphere-scale or similar scales, and these variations may be clues to broad-scale atmospheric or petrogenetic processes. At low elevations on Venus, the principal product of rock weathering is predicted to be ferric oxide (Fe₂O₃), the mineral hematite. However, it is not clear if the same mineral will be produced at high elevations – alternatives include magnetite (Fe₃O₄) and pyrite (FeS₂). The latter could be related to the “snow line” in the mountains of Ishtar Terra – above which the SAR backscatter is extremely high.

A similar puzzle is the pattern of radar backscatter with elevation at low latitudes, on near-equatorial highlands like Aphrodite Terra, and the mid-latitude volcanos of Tepev Mons – increasing radar backscatter to a critical elevation, and very low backscatter above that elevation. This pattern has been ascribed to presence of the ferroelectric substance chlorapatite, but this needs to be tested, both as to the properties of chlorapatite and the halogen chemistry of Venus’ near-surface atmosphere. And it is not obvious why this ferroelectric pattern does not also appear on the northern highlands of Ishtar Terra.
Studies of global patterns, such as weathering products, would require assets with global scope, such as are afforded by orbiters. Orbital radar, with higher spatial resolution and better resolution of surface electrical properties, would help explain the altitude (and latitude) effects on radar emissivity and reflectance. Orbital NIR emittance (as in the VIRTIS instrument on Venus Express) could in theory map the extent of hematite (as a weathering product) across Venus, in addition to its other mineralogical uses. These broad-scale remote sensing measurements would be augmented and improved by comparable measurements at greater resolution (but smaller extent) as from balloon assets; and ultimately by landed assets to provide ground truth.

**Investigation IIIC3.** Characterize the coupling of spin states (angular momentum) among Venus’ core, mantle and crust, and atmosphere, and how this coupling has affected Venus’ evolution.

Standard theory attributes the slow, retrograde rotation of Venus to a balance between two different solar tidal torques. Thermal tides on the atmosphere tends to increase the rotational rate, while the gravitational solid body tide acts in opposition. This balance is expected to shift over million-year timescales as the eccentricity of Venus’ orbit changes because these torques have different dependencies on the distance between Venus and the Sun. At much shorter timescales, irregularities in the rotation rate of Venus constrain models of its interior structure and the mechanisms that exchange angular momentum between the atmosphere and solid body. This investigation thus complements other investigations focused on the internal structure of Venus and understanding atmosphere/surface interactions and climate history.

Different models for the structure of the mantle and core predict variations in the rotation rate over one Venus day with amplitudes up to several minutes. Over decades, the length of day may also change by several minutes depending on the dynamics of the atmosphere and angular momentum exchange (e.g., a recent study argued that mountain waves substantially contribute to the total atmospheric torque on the surface and thus affect the rotation rate). Precisely measuring the Venus spin precession over decades would provide a direct measurement of the polar moment of inertia, an unmeasured yet fundamental constraint on interior models (e.g., to determine the size of the core). Excitingly, True Polar Wander (TPW) may occur quite rapidly (up to ~1 m/yr) on Venus relative to Earth and Mars because the rotational bulge in the solid body is tiny. Large volcanic eruptions or mantle convection could provide enough mass redistribution to provoke an episode of TPW.

Length-of-day variations may be constrained over decadal timescales even without spacecraft missions. In fact, neither Magellan nor Venus Express precisely measured the instantaneous length of day for Venus. Presently, the only combination of ground-based instruments capable of providing instantaneous length-of-day measurements—and, over time, estimates of the spin precession rate—are the 70-m antenna at Goldstone, CA and the 100-m telescope at Green Bank, WV. Both receivers observe radar echoes from Venus, which are correlated with a time delay that depends on the orientation and magnitude of the spin vector of Venus. Each spin measurement requires about an hour of telescope time; roughly thirty individual measurements per year are necessary to complete the investigation. Spacecraft missions could precisely track the location of surface features to reveal irregularities in the rotation rate at timescales of days to years. Topographical features are identifiable in thermal emission, although radar (or, below the clouds, visible) imagery may provide
better spatial resolution.
Table 2. Correlation of Investigations in Current and 2016 versions of the VEXAG GOI.

<table>
<thead>
<tr>
<th>Investigation in Current GOI</th>
<th>Investigation in 2016 GOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA1. Determine the isotopic ratios and abundances of D/H, noble gasses, and other elements in Venus’ atmosphere to constrain its planetary accretion, atmospheric evolution, and the possibility of ancient habitability.</td>
<td>IA1, IA2, IC1, IC4, IIA2, IIIA1, IIB1, IIB3, IIB4</td>
</tr>
<tr>
<td>IA2. Determine whether Venus shows evidence for abundant silicic (granitic) igneous rocks and/or ancient sedimentary rocks (including carbonates), as markers for abundant liquid water in its past.</td>
<td>IIB, (IIIA2, IIIA3)</td>
</tr>
<tr>
<td>IA3. Characterize the processes by which the atmosphere of Venus has evolved (gains, losses, &amp; changes) over time, including effects of magnetic fields, and incident ions and electrons</td>
<td>IA2, IC2, IIB1</td>
</tr>
<tr>
<td>IA4. Determine the structure and thermal state of Venus’ mantle, and the size and physical state of the core to place constraints on its accretion and early differentiation.</td>
<td>IIB4</td>
</tr>
<tr>
<td>IA5. Search for remanent magnetism in Venus’ surface rocks, to constrain past tectonic regimes, composition of the core, and to climate regimes related to atmospheric loss processes.</td>
<td>none</td>
</tr>
<tr>
<td>IB1. Investigate Venus’ unique volcano-tectonic surface features (e.g., coronae, tesserae, rigid block &amp; mobile belts) at improved spatial and topographic resolution, to determine which physical parameters allowed them to develop on Venus, and when in Venus’ geologic history these conditions were present.</td>
<td>IIA1 (IIA4)</td>
</tr>
<tr>
<td>IB2. Determine the current physical and thermal states of Venus’ crust and upper mantle (e.g., mobility, spatial variability) to constrain past processes (e.g., crustal overturn) and for comparison to other planets.</td>
<td>IIB3, IIB5, IIB6</td>
</tr>
<tr>
<td>IB3. Determine if Venus transitioned over time among multiple tectonic regimes reflecting mantle processes), e.g., mobile, stagnant or episodic lid models, and/or other modes of mantle cooling (e.g., heat pipe, squishy lid), and what physical parameters govern(ed) such global transitions.</td>
<td>IIA3, IIB3, IIIA2</td>
</tr>
<tr>
<td>IB4. Determine Venus’ abundances and distributions of heat-producing and volatile elements (in crust, mantle, core), and how abundances and distributions influence differentiation, crust formation and rheology on Venus and other planets.</td>
<td>IIB5</td>
</tr>
<tr>
<td>IB5. Determine the atmospheric properties of Venus that could be observable remotely by current and planned exoplanetary telescopes to constrain whether Venus (and Earth) represent typical or unique stages in planetary evolution.</td>
<td>none</td>
</tr>
<tr>
<td>IIA1. Characterize the dynamics of Venus’ lower atmosphere (below about 75km), including: the nature of the retrograde zonal super-rotation, the magnitude of the meridional circulation, radiative balances, generation of mountain waves, and interactions at Venus’ surface that affect the planet’s rotation rate.</td>
<td>IB1</td>
</tr>
<tr>
<td>IIA2. In Venus’ upper atmosphere and thermosphere, determine the role of solar-atmosphere interactions by characterizing global atmospheric dynamics and the space environment, including the effects of the space weather (fields and charged particles) environment.</td>
<td>IB1, IB2</td>
</tr>
<tr>
<td>IIIA3. Determine the role of the modes of mesoscale dynamics in redistributing energy and momentum throughout the four-dimensional Venus atmosphere system</td>
<td>IB3, IB1</td>
</tr>
<tr>
<td>IIB1. Characterize Venus’ atmospheric radiative balance, and the nature of the physical, chemical, and possible biological interactions among the constituents of the Venus atmosphere, the associated radiative interactions, and the atmospheric dynamics.</td>
<td>IB2, IC4, (IC3)</td>
</tr>
<tr>
<td>IIB2. Determine the physical characteristics and chemical compositions of aerosols in Venus atmosphere as they vary with elevation, including discrimination of aerosol types/components</td>
<td>IIA2, IIA4, IIB1, IIB4, (IC3)</td>
</tr>
<tr>
<td>IIB3. Determine the identity of the unknown shortwave absorber in Venus’ upper atmosphere, and the nature and magnitude of its influence on both local and global environments.</td>
<td>IB2, IC2, (IC3)</td>
</tr>
<tr>
<td>IIB4. Assess Venus’ surface-atmosphere chemical interactions by determining the composition of, and chemical gradients in, Venus' atmosphere from the ground surface up to the cloud base, both at selected locations and in global perspective.</td>
<td>IIIB3, IIIB1, IIIB2</td>
</tr>
<tr>
<td>IIB5. Determine the products of volcanic outgassing on Venus, and rates of outgassing to constrain its effects on atmospheric composition.</td>
<td>IC1</td>
</tr>
<tr>
<td>IIIA1. Search for current volcanic, tectonic, and sedimentary activity on Venus, including: active deformations; eruptions and thermal anomalies; and sediment deposition and erosion. Compare current levels and rates of activity with evidence of that in the past, and evaluate from them current resurfacing rates.</td>
<td>IIIA4, (IIIA3)</td>
</tr>
<tr>
<td>IIIA2. Determine elemental chemistry, mineralogy, and rock types on Venus’ surface, both at critical localities (e.g., tesserae) and globally, to understand the compositional diversity and origin of the crust.</td>
<td>IIB1, IIB2, (IIIA3)</td>
</tr>
<tr>
<td>IIIA3. Determine the structure and thickness of Venus’ crust, in three dimensions, to constrain lithospheric structure and processes and crustal volume.</td>
<td>IIB3, IB6</td>
</tr>
<tr>
<td>IIIA4. Search for structural, geomorphic, and chemical evidence of crustal recycling.</td>
<td>(IIB3, IIB6)</td>
</tr>
<tr>
<td>IIIA5. Constrain Venus’ interior (i.e, mantle &amp; core) processes that drive current and recent geologic activity.</td>
<td>IIB4,</td>
</tr>
<tr>
<td>IIB1. Constrain Venus’ average surface age, and relative ages of surface units, by evaluating impact cratering rates &amp; distributions, the relationship between impactor properties and crater morphology, and the processes that modify craters and their extended ejecta.</td>
<td>IIA1</td>
</tr>
<tr>
<td>IIB2. Determine absolute (radiometric) ages for Venus rocks at locations that are key to understanding the planet's geologic history.</td>
<td>IIA5</td>
</tr>
<tr>
<td>IIBC1. Evaluate the mineralogy, oxidation state, and changes in chemistry of Venus’ surface-weathered rock exteriors, (including thicknesses of rock weathering rinds), at localities representative of global geologic units.</td>
<td>IIB2, (IIIA3)</td>
</tr>
<tr>
<td>IIBC2. Determine the causes and spatial extents of global weathering regimes on Venus.</td>
<td>IIIB2</td>
</tr>
<tr>
<td>IIBC3. Characterize the coupling of spin states (angular momentum) among Venus’ core, mantle and crust, and atmosphere, and how this coupling has affected Venus’ evolution.</td>
<td>none</td>
</tr>
</tbody>
</table>
Table 3. Mapping of Decadal Survey themes to Objectives shown in the VEXAG GOI (Table 1).

<table>
<thead>
<tr>
<th>Decadal Survey Crosscutting Science Theme</th>
<th>Relevant Venus Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building new worlds</td>
<td>IA, IB</td>
</tr>
<tr>
<td>Planetary Habitats</td>
<td>IIB</td>
</tr>
<tr>
<td>Workings of Solar Systems</td>
<td>All Objectives</td>
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<td><strong>Decadal Survey Inner Planets Research Goals</strong></td>
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<tr>
<td>Origin and diversity of terrestrial planets</td>
<td>IB</td>
</tr>
<tr>
<td>Origin and evolution of life</td>
<td>IIB</td>
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<tr>
<td>Processes that control climate</td>
<td>IIA, IIB</td>
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The Importance of Basic Planetary Processes
While not specifically contained in Table 1, general studies of basic planetary processes will be a vital component of future Venus exploration. To elaborate, by “studies of basic planetary processes” we mean the study of features on a planet in order to obtain general knowledge about the processes that form those features; for example, studying the volcanoes on a planet in order to improve knowledge of physical volcanology. The Solar System can be considered as a natural laboratory to study a variety of physical processes under different temperatures, surface gravities, compositions, and so on. We could construct an entire separate table regarding the contributions that Venus exploration can make to understanding geologic and atmospheric processes, but we choose here to illustrate the point with a few particularly salient examples. At a time when CO$_2$ concentrations in Earth’s atmosphere are steadily increasing, it is important to study the interactions between radiatively active atmospheric constituents in planets other than our own in order to gain a better understanding of the feedbacks present in planetary atmospheres. The general gain in understanding of atmospheric chemistry and dynamics from examining Venus can improve our capability to accurately model Earth’s (and Titan’s) atmosphere and future climate. On Earth, there are no impact structures more than a few kilometers in diameter that are not either buried or significantly eroded. This makes Venus critical for studies of impact cratering mechanics, as it is the only planetary surface that provides examples of pristine impact craters that formed in Earth-similar gravity. In the field of volcanology, we have less data and consequently less understanding of submarine volcanoes on Earth relative to subaerial features. The dense atmosphere on Venus creates surface density and pressure conditions for volcanism that are intermediate to Earth’s subaerial and submarine conditions. Finally, we note that geologic features from Earth’s Archean period are all heavily eroded; there may be well-preserved analogs on Venus. Thus, Venus may enhance our understanding of this period on Earth when it is thought that lithospheric conditions were different from the present day.

Relationship of this Report to Other VEXAG Documents
As we discuss above in the Introduction, the Objectives and Investigations are prioritized in a manner that intrinsically provides weighting based on feasibility and costs. This document does not, however, explicitly weight the state of existing technology, potential instrument/mission costs, and science priorities in order to prioritize potential future instruments and missions. Furthermore, we do not make any statements regarding the temporal order in which future missions might be carried out (e.g., one mission uses a suite of instruments to reconnoiter a landing site for a subsequent mission). These activities are the focus of a separate VEXAG document titled Roadmap for Venus Exploration. That document essentially takes the output of the Goals, Objectives, and Investigations document and uses it as input to develop a viable unmanned exploration program consistent with the state of existing technology. As a planetary body, Venus poses some significant challenges for exploration. While many valuable
missions can be accomplished with current technology, some missions that could provide high science
Goals, Objectives, and Investigations for Venus Exploration return require technologies that have yet to
be developed. In particular, the high-temperature, dense, caustic atmosphere makes it very difficult to
have long-lived sub-orbital missions (e.g., landers, rovers) with existing technology. A separate
document, entitled Venus Technology Plan, lays out a viable technology development program whose
realization could significantly enhance our capability to explore Venus.

Document History
The Goals, Objectives, and Investigations for Venus Exploration, also known as the VEXAG Goals
Document, is a living document that is updated as needed by the Venus science community. The original
document was created in 2007 and was derived from extensive community input and discussions at open
meetings. Proposed revisions to the VEXAG Goals resulting from the Venus Flagship mission concept study in 2008–2009 were discussed and adopted by the VEXAG in 2009. This report represents a
substantial revision to the 2009 Goals Document. The revisions, initiated at the November 2012 VEXAG
meeting, included suggestions for a restructuring of the top-level Goals and reassessment of investigation
priorities. The process for making revisions included an extended period where community input was
solicited both online and through town hall meetings. Small changes to the 2012 document were added in
2016. The current GOI document represents a substantial revision to the 2016 GOI.

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