

Goals, Objectives and Investigations for Venus Exploration 2013

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 (TESS)] 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 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 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 atmospheric formation, evolution, and climate history on Venus.
2. Determine the evolution of the surface and interior of Venus.
3. Understand the nature of interior-surface-atmosphere interactions over time, including whether liquid water was ever present.

We describe each of these Goals in separate sections below. We have identified a small number of prioritized Objectives within each Goal that are stated as scientific questions. Table 1 links the Venus exploration Objectives back to the relevant themes of the Decadal survey. We present a set of prioritized Investigations designed to provide answers to the questions posed by each Objective.

Table 1. Mapping of Decadal Survey themes to Objectives shown in the Goals, Objectives, Investigations table (Table 2).

Decadal Survey Crosscutting Science Theme	Relevant Venus Objectives
Building new worlds	I.A, II.B, III.A
Planetary habitats	I.A, I.C, III.A, III.B
Workings of solar systems	All Objectives
Decadal Survey Inner Planets Research Goal	
Origin and diversity of terrestrial planets	All Objectives
Origin and evolution of life	I.A, I.C, II.A, III.A, III.B
Processes that control climate	I.A, I.B, I.C, II.A, III.A, III.B

We note that the Objectives and Investigations are prioritized in a manner that intrinsically provides weighting based on feasibility and costs. Investigations that cannot be conducted with current or foreseeable technology are excluded from this document. For example, investigations that would require returning surface samples to Earth were not considered. Investigations that are within the realm of possibility but would require significant technology development were weighted lower. For example, determining the absolute age of surface samples would be extremely valuable, but significant technology development is required for this capability to exist, so its overall priority is not high.

Table 2. VEXAG Goals, Objectives and Investigations		
Goals are not prioritized; Objectives and Investigations are in priority order.		
Goal	Objective	Investigation
I. Understand atmospheric formation, evolution, and climate history on Venus	A. How did the atmosphere of Venus form and evolve?	1. Measure the relative abundances of Ne, O isotopes, bulk Xe, Kr and other noble gases to determine if Venus and Earth formed from the same mix of solar nebular ingredients, and to determine if large, cold comets played a substantial role in delivering volatiles.
		2. Measure the isotopes of noble gases (especially Xe and Kr), D/H, $^{15}\text{N}/^{14}\text{N}$, and current O and H escape rates to determine the amount and timeline of the loss of the original atmosphere during the last stage of formation and the current loss to space.
	B. What is the nature of the radiative and dynamical energy balance on Venus that defines the current climate? Specifically, what processes control the atmospheric super-rotation and the atmospheric greenhouse?	1. Characterize and understand the atmospheric super-rotation and global circulation, including solar-anti- solar circulation above ~90 km and planetary-scale waves, by measuring the zonal and meridional wind structure and energy transport from the equator to polar latitudes and over time-of-day from the surface to ~120 km altitude. Use global circulation models to comprehensively connect observations acquired over different epochs, altitudes, and latitudinal regions.
		2. Determine the atmospheric radiative balance and the atmospheric temperature profile over latitude and time-of-day, from the surface to ~140 km altitude, in order to characterize the deposition of solar energy in the cloud layers and re-radiation from below, including the role of the widespread UV absorber(s).
		3. Characterize small-scale vertical motions in order to determine the roles of convection and local (e.g., gravity) waves in the vertical transport of heat and mass and their role in global circulation.
	C. What are the morphology, chemical makeup and variability of the Venus clouds, what are their roles in the atmospheric dynamical and radiative energy balance, and what is their impact on the Venus climate?	1. Characterize the dynamic meteorology and chemistry of the middle cloud layer through correlated measurements of formation and dissipation processes over all times-of-day and a range of latitudes. Analyze cloud aerosols, including their particle sizes, number/mass densities, bulk composition, and vertical motions. Study the abundances of their primary parent gaseous species, such as SO_2 , H_2O , and H_2SO_4 , as well as minor cloud constituents, such as S_n and aqueous cloud chemical products.
		2. Determine the composition, and the production and loss mechanisms, of "Greenhouse" aerosols and gases, including sulfur-cycle-generated species and UV absorbers, and their roles in the cloud-level radiative balance.
		3. Characterize lightning/electrical discharge strength, frequency, and variation with time of day and latitude. Determine the role of lightning in creating trace gas species and aerosols.
		4. Characterize biologically-relevant cloud and gas chemistry, including $^{13}\text{C}/^{12}\text{C}$ and complex organic molecules

Table 2 (cont.). VEXAG Goals, Objectives and Investigations

Goals are not prioritized; Objectives and Investigations are in priority order.

Goal	Objective	Investigation
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<p style="writing-mode: vertical-rl; transform: rotate(180deg);">II. Determine the evolution of the surface and interior of Venus</p>	<p>A. How is Venus releasing its heat now and how is this related to resurfacing and outgassing? Has the style of tectonism or resurfacing varied with time? Specifically, did Venus ever experience a transition in tectonic style from mobile lid tectonics to stagnant lid tectonics?</p>	<ol style="list-style-type: none"> 1. Through high-resolution imaging and topography, characterize the stratigraphy and deformation of surface units in order to learn the sequence of events in Venesian geologic history. This includes assessing any evolution in volcanic and tectonic styles and analyzing any evidence of significant past horizontal surface movement. 2. Characterize radiogenic ^4He, ^{40}Ar and Xe isotopic mixing ratios generated through radioactive decay to determine the mean rate of interior outgassing over Venus's history. 3. Combine geophysical measurements with surface observations to characterize the structure, dynamics, and history of the interior of Venus and its effects on surface geology. Relevant geophysical approaches include, but are not limited to, gravity, electromagnetics, heat flow, rotational dynamics, remanent magnetization, and seismology. 4. Determine contemporary rates of volcanic and tectonic activity through observations of current and recent activity, such as evaluating thermal and chemical signatures, repeat-image analysis, ground deformation studies, and observations of outgassing. 5. Determine absolute ages for rocks at locations that are key to providing constraints on global resurfacing rates.
	<p>B. How did Venus differentiate and evolve over time? Is the crust entirely basaltic, or are there significant volumes of more differentiated (silica-rich) crust?</p>	<ol style="list-style-type: none"> 1. Determine elemental composition, mineralogy, and petrography of surface samples at key geologic sites, such as the highlands tesserae, in order to understand the compositional diversity and origin of the crust. 2. Determine compositional information for rocks at regional scales using remote sensing to gain a global scale picture of geochemical processes. 3. Determine the structure of the crust, as it varies both spatially and with depth, through high-resolution geophysical measurements (e.g., topography and gravity, seismology), in order to constrain crustal volume and lithospheric structure and processes. 4. Determine the size and state of the core and mantle structure (e.g., via geodesy or seismology) to constrain early differentiation processes and thermal evolution history. 5. Constrain the radiogenic element content of the crust to better constrain bulk composition, differentiation and thermal evolution. 6. Characterize subsurface layering and geologic contacts to depths up to several km to enhance understanding of crustal processes.

Table 2 (cont.). VEXAG Goals, Objectives and Investigations		
Goals are not prioritized; Objectives and Investigations are in priority order.		
Goal	Objective	Investigation
III. Understand the nature of interior-surface-atmosphere interactions over time, including whether liquid water was ever present.	A. Did Venus ever have surface or interior liquid water, and what role has the greenhouse effect had on climate through Venus' history?	1. Determine the isotopic ratio of D/H in the atmosphere to constrain the history of water. Determine isotopic ratios of $^{15}\text{N}/^{14}\text{N}$, $^{17}\text{O}/^{16}\text{O}$, $^{18}\text{O}/^{16}\text{O}$, $^{34}\text{S}/^{32}\text{S}$, and $^{13}\text{C}/^{12}\text{C}$ in the atmosphere to constrain paleochemical disequilibria.
		2. Identify and characterize any areas that reflect formation in a geological or climatological environment significantly different from present day. Determine the role of water in the formation of highlands tesserae.
		3. Search for evidence of hydrous minerals and of greenhouse gases trapped in surface rocks in order to understand changes in planetary water budget and atmospheric composition over time.
	B. How have the interior, surface, and atmosphere interacted as a coupled climate system over time?	1. Characterize elemental composition and isotopic ratios of noble gases in the Venus atmosphere and in solid samples, especially Xe, Kr, ^{40}Ar , ^{36}Ar , Ne, ^4He , and ^3He , to constrain the sources and sinks that are driving evolution of the atmosphere, including outgassing from surface/interior.
2. Evaluate the characteristics of weathering rinds, and determine the mineralogy and composition of rocks beneath any weathering rind, in order to constrain resurfacing rates, past weathering processes, the composition of unweathered rocks, and possible implications for past climate conditions.		
3. Determine the abundances and altitude profiles of reactive atmospheric species (OCS , H_2S , SO_2 , SO_3 , H_2SO_4 , S_n , HCl , HF , ClO_2 and Cl_2), greenhouse gases, H_2O , and other condensables, in order to characterize sources of chemical disequilibrium in the atmosphere and to understand influences on the current climate.		
4. Determine the atmospheric/surface sulfur cycle by measurements of the isotopic ratios of D/H, $^{15}\text{N}/^{14}\text{N}$, $^{17}\text{O}/^{16}\text{O}$, $^{18}\text{O}/^{16}\text{O}$, $^{34}\text{S}/^{32}\text{S}$, $^{13}\text{C}/^{12}\text{C}$ in solid samples and atmospheric measurements of SO_2 , H_2O_2 , OCS , CO , $^{34}\text{S}/^{32}\text{S}$ and sulfuric acid aerosols (H_2SO_4), to determine, in particular, the current rate of sulfur outgassing from the surface.		

Goal I – Atmospheric Formation, Evolution, and Climate History

Goal I is to understand the atmosphere, its current processes, how it has influenced the past climate history on Venus, and what that says about our own climate today. The objectives highlighted in this goal focus on key issues that still remain after more than 50 years of solar system exploration. We want to understand how the atmosphere formed initially under seemingly Earth-like conditions and how it evolved to the extremely un-Earth-like Venus we see today. Detailed chemical measurements of the composition of the atmosphere (in particular, the noble gases and their isotopes) provide crucial information about the origin and evolution of Venus. Understanding the energy deposition across the planet at all altitudes, and how that energy is absorbed and redistributed by the clouds and the dry atmosphere is key to understanding the planet's surprisingly dynamic global circulation – including the high-speed super-rotating zonal winds that blow more than fifty times faster than the spin of the planet – and provides critical constraints for atmospheric models. These models can then be used to project through the climate history of Venus, and inform us on our own climate history (Goal III). This also contributes to understanding processes that subsequently modified the secondary (or original) atmosphere, leading to the current inventory of atmospheric gases that is so dissimilar to those present on Earth today.

A. Atmospheric Formation and Evolution

How did the atmosphere of Venus form and evolve?

Understanding Venus' origin, formation and evolution is key to understanding how all the terrestrial planets formed and evolved, as well as how Venus' current exotic environment came to be. Venus today is bone-dry, enshrouded by a 90-bar-thick CO₂ atmosphere with high-opacity sulfuric acid clouds, more than 99.5% of which whirls around the planet at a rate faster than the solid planet, a property called super-rotation. The mass density and speed of these winds exceeds hurricane force from a few kilometers above the surface to the cloud tops around 70 km. Despite the fact that reflective clouds expel most of the sunlight back to space, the surface is nevertheless warmed to over 735 K, hotter than the mean surface temperature of any planet, including Mercury. Just how did such a rather bizarre global climate come to be?

Understanding the origin of Venus is the first step. First, did the planet form from the same mix of solar nebular ingredients as the other terrestrial planets, or did it form in a different mixture, perhaps infused with different bulk materials? Measurements of the three isotopes of neon and oxygen can help to answer that question, providing crucial information about the radial gradients in the accretion sources of volatiles in the inner solar system and the amount of mixing during this stage that can be used to constrain models of the formation of Earth, its moon, and Mars. Was there originally a large reservoir of water on Venus that later was eroded

away? If so, were such volatiles delivered by large cold comet-like planetesimals from the outer solar system, as postulated for Earth? Measurements of the abundances of the bulk noble gases – in particular xenon and krypton - can help deduce the answer [I.A.1]. As is the case for Mars and Earth, did Venus lose its original atmosphere? If so, was it from (1) the intense solar flux at extreme ultraviolet wavelengths of the Sun's T-Tauri phase during the first 100 Myr of the planet's existence or from (2) giant collisions during the late heavy bombardment phase some 500 to 700 Myr later? Analysis of the eight non-radiogenic isotopes of xenon, the heaviest of the noble gases, together with measurements of the radiogenic isotope ^{129}Xe can provide definitive answers, while also providing evidence for the importance of such mechanisms in stripping away the original atmospheres of both Earth and Mars. In addition, measurements of the nitrogen isotope ratio $^{15}\text{N}/^{14}\text{N}$ provide further insight into the loss of Venus' atmosphere [I.A.1; I.A.2].

As the atmosphere of Venus evolved over the aeons, it lost most of its water to space, as evidenced by the extremely large D/H found today – some 150 times that found in Earth's oceans - and the small abundance of water vapor in the atmosphere – 30 ppm vs ~30,000 ppm found in the terrestrial atmosphere below its condensation level, which itself comprises just 0.001 percent of the terrestrial water inventory when oceans, icecaps, glaciers and ground water are taken into account. This loss of water transformed Venus, changing its clouds, chemistry, climate and – by starving the interior of the lubricating effects of hydrated rocks – its geology. Just how fast was this water lost? Direct in-situ measurements of water and deuterium escaping the planet from orbit under different solar flux conditions during the solar cycle and during intense solar storms – such as currently occurring and being observed by Venus Express - can provide insight that could be modeled over the aeons. As well, measurements of D/H as a function of altitude can give us additional insight into the current rate of water loss, averaging over short-term solar effects [I.A.2].

B. Energy Balance, Super-Rotation and Greenhouse

What is the nature of the radiative and dynamical energy balance on Venus? Specifically, what processes control the atmospheric super-rotation and the atmospheric greenhouse?

The understanding of the global planetary energy budget is key to unraveling the secret inner workings of Venus's current atmosphere and climate. Despite being 30% closer to the Sun than the Earth, Venus absorbs less solar flux, as 75% of this flux is reflected by the global system of clouds. Of the remaining solar flux, half is absorbed within the cloud layer by gaseous CO_2 , SO_2 , and an unidentified compound entrained within and above the clouds that absorbs UV. Only 2.6% of the incident solar flux reaches the surface. This makes Venus unique among the terrestrial planets with an atmosphere being heated from above, rather than from the surface below as is the case with the Earth and Mars. To understand Venus's energy balance, it is

crucial to understand the temperature profile changes with altitude, latitude, and longitude at various timescales [I.B.2]. Mesospheric thermal profiles from the cloud tops (~70 km) to 100 km show strong gradients, with the poles being surprisingly warmer (~20 K) than the equator. The observed instability of the vertical temperature profile within the clouds and the detection of atmospheric scintillations above the clouds, show that convection and wave propagation play significant roles in the energy and momentum balance in the atmosphere of Venus. However, the mesoscale (regional-scale) dynamics of Venus remain inadequately characterized to explain the variability seen, and the effects of wave activity in the atmosphere of Venus (transport of energy and momentum, including wave breaking, interactions with the clouds, etc.) remain to be measured. In the lower atmosphere, the greenhouse effect keeps the surface at ~735 K, producing near-infrared thermal emissions that heat the lower cloud. The energy budget also varies with time. The unknown UV absorber that modulates much of the energy balance at the cloud tops has large observed changes in its spatial distribution over short timescales, sometimes accompanied by abrupt brightening events that dramatically alter the global albedo of Venus [I.B.2].

The radiative balance process ultimately, and most spectacularly, manifests itself as the super-rotation of the global atmosphere, where prograde zonal winds (East to West, corresponding to the direction of planetary spin) move with speeds greater than the surface rotational speed at all altitudes, and with speeds in excess of 120 m/s at the cloud tops. This is accompanied by meridional wind motion that transports heat and momentum from equator to the poles, producing compressional heating at the poles. How do these winds change over time, by how much, and what consequences does it have on the global energy budget [I.B.1]? Long term, high-resolution measurements of temperatures and wind speeds at multiple altitudes and locations are needed to answer this question. Solar tides are also likely to be important for redistributing heat and momentum. Diurnal, semi-diurnal and quarter-diurnal thermal tides have been observed in the mesosphere and at the cloud-tops. These tides are correlated to solar time showing the importance of shortwave (or solar) heating. More observations are needed to determine their impact on heat and momentum transport and to disentangle their effect from other possible dynamical mechanisms driving the global super-rotation [I.B.1]. Included among these are small-scale vertical motions driven by local (e.g. gravity) waves and convection. Observations of these effects over latitude and times of day in the clouds are needed to inform the importance of such mechanisms in the vertical transport of heat and mass and their role in global circulation [I.B.3].

Perhaps nothing epitomizes the divergent evolutionary paths taken between Earth and Venus more than the atmospheric greenhouse effect. To balance out the incoming solar flux, the atmosphere re-emits in the infrared and surface temperatures reach 735K. A significant effect in atmospheric heating is from water vapor (increasing the effective temperature by ~70 K), but

it is present only in small amounts (~ 30 ppmv) in the atmosphere. Understanding the variability and chemical reactions of H_2O is critical to understanding the greenhouse effect on Venus. In addition, the effect of the variability of other minor gaseous species and cloud microphysics on the radiative forcing needs to be addressed. We also need a better understanding of how this radiative forcing leads to and affects the general circulation of the atmosphere we see today. What are the various sources and sinks within the atmosphere that affect the dynamics of the circulation? These questions are prevalent in the terrestrial climate community and are equally vital in the study of Venus's climate [I.B.1]. Finally, understanding the evolution of the greenhouse effect through Venus's history and its effect on atmospheric circulation is key to understanding how Venus diverged in its prior epoch.

C. Clouds and Lightning

What is the morphology and chemical makeup of the Venus clouds, and what are their roles in the atmospheric dynamical and radiative energy balance?

The basic knowledge of the Venus aerosols was established in the 1970's with the identification of two modes of aerosols with sizes on the order of $0.1 \mu\text{m}$ and $1.0 \mu\text{m}$ composed of highly concentrated sulfuric acid determined from polarimetry. Subsequent observations established sulfuric acid as the primary constituent also of the clouds deeper than one optical depth, and identified three distinct size modes of cloud aerosols, but several questions remained. A larger mode of aerosols with radii of several μm to tens of μm was identified that could not be reconciled as being sulfuric acid. The identity (and in fact the existence) of this third mode of particles remains unknown [I.C.1]. The confidence level of the characterization of the smallest mode of aerosols in the polar regions is high; but the contribution by these haze particles to the polarimetry in the equatorial regions was small enough that their identification as sulfuric acid could not be established as firmly as for their polar counterparts [I.C.1]. An ultraviolet absorber, in addition to confirmed sulfur oxides such as SO_2 , SO , and OCS , was identified to exist in the upper clouds of Venus. Numerous candidates have been suggested, with varying levels of consistency with the observations, but the identity of this absorber remains unknown [I.C.1].

The aerosols play a significant role in the radiative balance of Venus. The sulfuric acid aerosols are highly reflective in ultraviolet and visible wavelengths, and hence are responsible for the very high albedo of Venus (as discussed in the previous section, despite being closer to the Sun, Venus absorbs less solar flux than does the Earth). SO_2 and the unknown ultraviolet absorber are so radiatively active that most of the solar radiation that is not reflected away by those aerosols is absorbed in the upper clouds of Venus. The sulfuric acid is produced photochemically in the upper atmosphere from a series of potential chemical pathways involving SO , SO_2 , OCS , and H_2O , the rates of which are affected by the local chemical

abundances as well as dynamical and thermal conditions. Thus, understanding the chemical and microphysical cycles that couple the absorbing gaseous sulfur species and their associated aqueous reflecting aerosol species (and potential absorbing contaminants that can be found within or upon those aerosols) is key for understanding the current and past radiative balance and greenhouse-driven climate of Venus [I.C.1; I.C.2]. Such understanding is significantly enhanced by correlated observations of the formation and dissipation processes of aerosols together with (1) their parent gas abundances and (2) local dynamic conditions (e.g., temperature and vertical flow) under varying solar lighting conditions of time-of-day (e.g., day vs. night) and latitude (e.g., polar vs. equatorial) [I.C.1].

The aerosols themselves could play significant roles in the study of two of the more controversial topics related to the Venus atmosphere, namely, lightning and biosignatures. Radio observations of lightning have been recorded by several orbiting and passing spacecraft, but significant non-detections have also been made. The existence of Venusian lightning remains to be confirmed optically, and a microphysical basis for the generation of lightning (while still poorly understood for Earth) also remains undetermined. However, the radio observations, especially from Venus Express, are significant, numerous, and persistent. Yet, due to effective shielding by the solar-wind-induced ionosphere and the highly inclined and elliptical orbit of the spacecraft, the tell-tale signatures of lightning observed by Venus Express can only be detected over a limited region of the north pole. Are these radio signatures associated with lightning, or do they have some other source? Radio/magnetometer observations conducted from within the atmosphere under the ionosphere could provide an unambiguous census of lightning frequency and strength, and correlate their variability with meteorological conditions as determined by local cloud mass and vertical dynamics, all over all times-of-day, to provide clear links between Venusian clouds and dynamics with lightning [I.C.3]. Even lacking radio/magnetometer or optical confirmation of lightning, the existence of compounds in the atmosphere of Venus that require energies comparable to lightning strikes for formation (such as nitrogen oxides), would provide a key measurement that would constrain the existence and frequency of lightning activity in the Venus atmosphere.

Regardless of whether organisms exist today in the clouds of Venus, the conditions for life there are very good for acidophilic organisms. Temperatures range from 360 K near cloud base (48 km near the equator) down to 230K near the tops of the clouds (70-72 km), and pressures range from 1.5 bars near cloud base down to 30 millibars near the cloud tops. Previous work has suggested that photolytic organisms are capable of surviving in the upper atmosphere of Venus, provided they are acidophilic as well. Characterization of biologically relevant cloud and gas chemistry, including $^{13}\text{C}/^{12}\text{C}$, could provide evidence of biological processes [I.C.4].

Goal II – Evolution of the Surface and Interior

The overarching question “why are Earth and Venus so different?” also arises for the surface and interior. Plate tectonics is the fundamental process that dominates geologic activity of Earth, controls its heat loss rate, and governs the cycling of volatiles from the interior to the surface and atmosphere. Some argue that the range of surface environments created by volatile cycles and altitude variations between ocean basins and continents are essential to the evolution of life on Earth. While some Venusian surface features are familiar from Earth, such as shield volcanoes, lava plains, fold belts, 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 distribution of surface elevations on Venus varies smoothly instead of being bimodally distributed by continent or ocean basin as on Earth. Venus has clear indicators of at least limited horizontal surface movement (e.g., rift zones, the tessera), but it does not have Earth-analogous morphologic indicators of an organized system of moving rigid lithospheric plates; i.e., plate tectonics. The production of new crust at mid-ocean ridges coupled with recycling of the lithosphere in subduction zones makes plate tectonics an effective mechanism for releasing interior heat on the Earth. While Venus does not seem to presently have plate tectonics, it is also difficult to reconcile existing geological and geophysical observations, especially with an Earth-similar level of heat release, with Venus as a long-term single-plate (or “stagnant lid”) planet. The impact record is particularly puzzling. The Magellan mission revealed less than a thousand impact structures on the surface of Venus, indicating a young surface age much closer to Earth's than the other, more heavily cratered inner solar system bodies. However, the distribution of those craters is quasi-random even though the distribution of other geologic features is nonrandom. A variety of un-Earthly convective models and planetary resurfacing scenarios have been proposed to explain existing observations, and only new data can generate breakthroughs in understanding.

Has the planet resurfaced primarily through volcanism, the dominant process evident on the surface today? Or 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 did not have past 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? These issues are the basis of the Objectives for Goal II.

A. Heat Release and Resurfacing

How is Venus releasing its heat now and how is this related to resurfacing and outgassing? Has the style of tectonism or resurfacing varied with time? Specifically, did Venus ever experience a transition in tectonic style from mobile lid tectonics to stagnant lid tectonics?

The gravitational energy released due to accretion and differentiation caused Venus to begin life with a very hot interior. The similarity in size and density of Venus and Earth suggests that the two planets should have similar heat sources. The decay of radioactive elements provides a continuing input of internal energy at a slowly declining rate. This heat is released to the surface over time by a combination of convective flow and conduction. The coupling of convective motions in the mantle to the crust and lithosphere drives many types of geologic processes, including volcanic eruptions, rifting, and the formation of mountain belts. The preservation of these structures in the crust provides clues for unraveling the evolution of Venus after its initial cooling.

There is currently no consensus on how the rate of resurfacing due to volcanism and tectonics has varied with time on Venus. Existing hypotheses range from a "catastrophic" resurfacing followed by minimal geologic activity to relatively steady-state behavior with time. Both current and past levels of geologic activity are hotly debated. Existing results leave many important but unanswered questions: How variable has resurfacing been over time, and what are the current levels of geologic activity? If there have been dramatic changes in the nature or rate of resurfacing, what physical processes in the mantle or lithosphere triggered the change? Did Venus ever have Earth-like plate tectonics or some other method of lithospheric recycling? What are the implications for outgassing of volatiles and the climate?

Many of the details of the surface geologic record that we need in order to test hypotheses are simply unobservable in our current imaging and topography data sets. Existing radar maps of Venus have resolutions of hundreds of meters, and global altimetry provides topography with a horizontal resolution of worse than ten kilometers. These data sets are roughly comparable to our knowledge of Mars in the 1970s. Much higher resolution radar imaging and topographic mapping is now possible, permitting better determination of geologic units and their stratigraphic sequence [II.A.1]. Examples of the kinds of key observations that we could make with better imaging and topography are delineating individual lava flows, mapping individual fault blocks, and characterizing the nature of geologic contacts between volcanic and structural units. If we can combine imaging and topography with geochemical and geophysical observations, then we can advance our knowledge of the interior and its relationship to surficial geology. The radioactive decay of heat producing elements in the Venus interior produces several noble gases as a by-product. These gases can escape to the atmosphere during volcanic activity, so measuring the isotopic mixing ratios of ^{40}Ar and ^{129}Xe in the atmosphere would

place constraints on the long-term volcanic outgassing rate on Venus, and measuring atmospheric ^4He would constrain the geologically recent outgassing rate [II.A.2].

Geophysical measurements can provide critical information about subsurface thermal and mechanical structure and how it varies both laterally and with depth. We can use this information not only to understand how current interior processes are affecting the surface, but also to unravel how interior evolution has caused the surface to change with time. The crust on Venus appears to be mostly or entirely igneous in origin, so measuring the thickness of the crust by seismology or gravity observations helps to determine the volume of volcanic activity over the history of the planet. Seismic measurements of the depth of phase transitions in the mantle or the physical state of the core (liquid or solid) and measurements of the heat flow out of the interior of Venus would constrain the present-day thermal structure of the Venus interior [II.A.3].

A key element of understanding Venus as a physical system is to determine the present level of geologic activity and, if possible, determine an absolute age for surficial geologic units. Analyses of radar emissivity data from Magellan and infrared emissivity data from Venus Express suggest that the planet has experienced recent volcanism, but there is not enough information to constrain current rates of resurfacing. If Venus has current volcanic or tectonic activity, it may be possible to detect this by observing changes in either radar images or surface topography over time, by the infrared signature of active lava flows, by the chemical signatures of volcanic outgassing, or by seismic detection of Venus quakes [II.A.4]. Measurement of the absolute radiometric age of even a few geologic units would place strong constraints on the geologic history, although the technical challenges of in-situ age dating on the Venus surface are formidable [II.A.5].

B. Internal Differentiation

How did Venus differentiate and evolve over time? Is the crust entirely basaltic, or are there significant volumes of more differentiated (silica-rich) crust?

Most known solid planets, satellites, and asteroids greater than several hundred km in size have undergone global chemical differentiation, in which various melting processes allow a body to separate, mainly by gravity, into masses of different composition. Rocky worlds naturally separate into a metallic core, an iron-magnesium-rich mantle, and a complex, outermost crust. Three broad stages of silicate crust formation are recognized. A primary crust is formed by nearly global melting and subsequent crystal fractionation during the late stages of planetary accretion. This is often referred to as a magma ocean. The lunar highlands comprise the only known preserved primary crust. Secondary crust forms by regional melting of the upper mantle: for silicate bodies, this crust is overwhelmingly basaltic for the simple reason that basalt is the product of pressure-release partial melting of the ferromagnesian mantles of the terrestrial

planets. Most of Earth's seafloor, the lunar maria, the lowlands and rolling plains of Venus, and the surfaces of Mars and Mercury are basaltic. The exact composition depends on the details of the initial composition, the temperature at which melting is initiated, and the degree of partial melting. Tertiary crust is the product of remelting pre-existing crust. On Earth, this occurs mainly at convergent plate margins where melting of the overlying mantle wedge is initiated by the release of water by dehydration of oceanic basaltic crust. Underplating and intrusion of continental crust may also form tertiary crust, but this is from prior tertiary crust. There is little evidence that remelting of dry basalt or peridotite alone can generate more evolved crust; the key to formation of higher-silica tertiary crust on Earth is the ability to recycle water-rich volatiles into the mantle. The unique tesserae of Venus have been hypothesized to be composed of evolved crust, based on their higher infrared emissivities and higher elevations/thicker crust in analogy with Earth's continents. The existence of substantial tertiary crust on Venus would then be tied to its history of crustal recycling and the evolution of water, important cross-cutting themes discussed elsewhere in this document.

The differentiation history of Venus can be understood by a combination of in situ measurements and remote sensing, the latter including geophysical measurements. With respect to understanding global surface composition, a standard planetary approach is to tie detailed point source measurements (i.e., lander measurements) to regional and global remote sensing information. "Ground truth" elemental composition, mineralogy, and petrology [II.B.1,5] require measurements at or very near to the surface and hence are point samples. Modern alpha-particle, x-ray, and gamma-ray instruments can greatly improve upon the early measurements of elemental composition performed by the Venera and Vega landers. Understanding the general elemental composition of surface rocks can, in many cases, allow inference of rock and mineral types and the physical processes that formed them. However, direct knowledge of how elements have been arranged into minerals (crystalline structures with defined chemical compositions) can provide substantially more information about the formation and evolution of crustal materials. X-ray diffraction can provide such analysis on powdered samples and has been performed in situ on other planets on the Mars Science Laboratory. The size and nature of mineral grains and their organization within a rock, i.e. the rock's petrology, provides additional unique information about the thermal and mechanical processes that have affected the rock. Microscopic imaging of rock surfaces or slices can identify many minerals directly, but more generally allows petrologic history to be determined. For example, the nature of grain contacts reveals whether a rock is crystalline (igneous/metamorphic) or sedimentary, and grain size in crystalline rocks varies inversely with cooling rate. Spectroscopy from balloons or orbit may also determine large-scale compositional variations [II.B.2]. Atmospheric absorption controls which parts of the electromagnetic spectrum can be used for remote sensing spectroscopy.

Geophysical methods can be used to build a fully three-dimensional understanding of the planet's chemical and mechanical structure. The crust [II.B.3,6], mantle, and core [II.B.4] can be probed by a variety of geophysical methods, e.g. (in approximate order of increasing exploration depth), magnetics, ground-penetrating radar, electromagnetics, gravity, and rotational dynamics. Seismology can be applied at a variety of scales depending on implementation. Each geophysical method is sensitive to a different set of rock properties (e.g., density, sound wave velocity, dielectric constant, porosity), so that the various approaches provide complementary data that can be combined to achieve a more comprehensive understanding of the subsurface. With the exception of ground-penetrating radar, all of these methods have passive modes and hence do not require transmitters. Magnetics is assigned the shallowest exploration depth here because the high surface temperature of Venus inhibits permanent rock magnetism. Although it is well known that gravity surveys can be carried out from the air or space, it is worth noting that there are comparable emerging techniques for electromagnetic and seismic investigations at Venus.

Goal III – Interior-surface-atmosphere interactions

Once the surface of a planet's magma ocean begins to freeze and the steam atmosphere has stopped losing molecules to space, a planet's inventory of volatiles and other gases are loosely locked in place. Volatiles are exchanged between the interior, surface, and atmosphere over time. Interior volatiles are outgassed to the surface via volcanism. Chemical evolution of the atmosphere changes the distribution of gases and some gases interact with the surface rocks to create new minerals. Light gases are especially prone to being eroded off the top of the atmosphere and can be permanently lost. This initial inventory of gases is critical for determining not only the characteristics of a planet's atmosphere – its composition, dynamics, and the extent of greenhouse warming – but also the composition of the surface, how easily volcanism occurs, the form of lithospheric deformation, and how readily its interior convects.

A. Liquid Water

Did Venus ever have surface or interior liquid water, and what role has the greenhouse effect had on climate through Venus' history?

Given their similarity in size, bulk composition and location in the solar system, did Venus and Earth start with similar initial volatile budgets? How has the volatile budget, particularly the water budget, changed with time? How did the resulting changes in atmospheric composition then affect the planet's greenhouse-driven climate, perhaps transitioning from a hospitable world of lakes and seas to the distinctly inhospitable world we see today?

Surface composition may record evidence of a past, water-rich period. Tesserae are massive, highly deformed plateaus that are among the most intriguing features on Venus, and may be

key to understanding the history of water [III.A.2]. Like Earth's continents, tesserae are supported by thick crustal roots and may be richer in silica than the surrounding plains. On Earth, the continents form via remelting of basalt in the presence of abundant water. Confirming the composition of tesserae plateaus as felsic (relatively silica-rich) would verify that Venus once had widespread crustal water.

In addition to surface composition, tectonic features may also record evidence of climate [III.A.2]. If Venus were resurfaced in a huge outpouring of volcanism in a relatively short time, the change in atmospheric composition would likely have resulted in dramatic changes in climate. Models predict that the surface may have been heated and cooled by more than 100°C. These changes are extreme enough to cause fracturing of rocks in response to thermal contraction and expansion. Tectonic features such as wrinkle ridges and massive polygons could be evidence of extreme climate-driven temperature changes.

Hydrated minerals or gases trapped in volcanic rocks could also illuminate past conditions [III.A.3]. On Earth, water is outgassed via volcanism and recycled back into the interior by subduction. Argon isotopes suggest that Earth has outgassed about 50% of its volatiles, but Venus has lost only 25%. Venus presents contradictory evidence about its interior volatile content. It has experienced massive volcanism over the last billion years, but whether this volcanism and its associated outgassing were rapid or gradual is uncertain. Once outgassing occurs, can volatiles be recycled back into the interior? Numerous studies suggest that the lithosphere of Venus is dry and strong, and that its upper mantle lacks a water-weakened low viscosity zone that may be a key factor in allowing plate motion on Earth. The present-day D/H ratio, and its vertical profile at high altitude above ~70 km, gives information on the current loss of hydrogen and thus water vapor. Near the surface, both the water abundance and the D/H ratio emitted by volcanoes would provide insights into the primordial water content of Venus and the degree of recycling by geologic processes such as subduction [III.A.1]. Determining the abundance of volatiles with time by investigating the chemical signatures of rates of outgassing today and in the past – via the light isotopes, water, argon, and helium – will help illuminate paleochemical equilibria below the surface and the processes that control the geologic evolution of Venus [III.A.1]. As well, such constraints would help illuminate the abundances of greenhouse gases and associated aerosols in the past, to understand the evolution of Venus' climate to the current environment of extreme surface temperature and optically-thick, 30-km-deep globe-encircling sulfuric acid clouds.

B. Interior-Surface-Atmosphere Interaction

How have the interior, surface, and atmosphere interacted as a coupled climate system over time?

We can investigate the atmosphere-surface-interior interaction with time by studying the evolution of atmospheric gases, their isotopic ratios, and evidence of interactions between the atmosphere, surface and interior. Sampling of the noble elements and their isotopes in the atmosphere and surface rocks constrain the sources and sinks - including outgassing from the surface/interior - that drive atmospheric evolution [III.B.1]. The abundances of sulfur and the sulfur isotopic ratios ($^{34}\text{S}/^{32}\text{S}$) emitted by volcanoes and other geologic processes provide key information on the rate of resupply of sulfur to the atmosphere [III.B.4]. As the building block of the clouds that are a prime control of Venus' climate, understanding the rate of surface sulfur emission, which is a function of the rate of surface volcanism, provides clues on Venus' climate and clouds over the eons. The formation of these clouds depends on intermediate steps involving numerous reactive species, notably involving oxygen and chlorine, that also contribute to the greenhouse environment [III.B.3].

A key question for understanding the chemical balance of the atmosphere is the degree to which it is buffered by chemical reactions with surface rocks [III.B.2]. Determining the current surface weathering reactions would also help constrain volcanic resurfacing rates. There are a variety of possible weathering reactions that may be taking place, involving different atmospheric gases and surface minerals. Although experiments and thermodynamic models have been conducted to attempt to simulate the weathering environment on Venus, lack of information on near surface atmospheric composition and oxidation state make it difficult to assess the most likely reaction. Evidence for relatively recent, unweathered volcanic flows suggests that chemical interactions are active today. If the rate of surface chemical weathering were known, it would be possible to estimate the age of these flows and thus the current rate of resurfacing. Simulating the surface conditions on Venus for long enough to measure reaction rates is challenging, but could be undertaken if specific reactions were identified. Investigating the composition of surface weathering products and for any change in composition of the weathering rind with depth will reveal the specific reactions and allow their rates to be determined. This would provide a boundary condition for current atmospheric chemistry. Changes in the composition of the weathering products with depth could provide evidence for past climate conditions and atmosphere composition.

The importance of basic planetary processes

While not specifically contained in Table 2, 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 CO₂ 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 Archaean period are all heavily eroded; there may be well-preserved analogs on Venus (for example, large radial dyke swarms). 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 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, titled “Technologies for Venus Missions to enable the VEXAG Goals and Objectives”, 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.