Short Course: Planetary Science of Venus, and the Promise of In Situ Sampling Techniques

Keck Institute for Space Studies

“Unobtainable” Venus Science

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“Unobtainable” Venus Science

1. What are the big science questions remaining for Venus?
2. What is considered a "feasible" architecture by VEXAG currently?
3. Which of the questions are not directly addressed with "Feasible" architectures?
4. What questions that are NOT called out in VEXAG that we would be asking if we thought we could?
5. What are the atmospheric/temperature environmental conditions that can be challenges/benefits for returning to upper atmosphere?

What are the big science questions remaining for Venus?

informed by

Obtainable Venus Science

The definition of “obtainable” (and “remaining”) has changed radically in the last two weeks.

Start by examining Venus science “**Goals, Objectives, and Investigations**” the community has been refining for the last 2+ decades.

Most of these are “feasible” today, but “obtainable” has been elusive

Goal	Objective	Investigation
I. Understand Venus' early evolution and potential habitability to constrain the evolution of Venus-size (exo)planets.	A. Did Venus have temperate surface conditions and liquid water at early times?	 
	B. How does Venus elucidate possible pathways for planetary evolution in general?	

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I. Understand Venus' early evolution and potential habitability to constrain the evolution of Venus-size (exo)planets.	A. Did Venus have temperate surface conditions and liquid water at early times?	**HO. Hydrous Origins (1).** Determine whether Venus shows evidence for abundant silicic igneous rocks and/or ancient sedimentary rocks.
		RE. Recycling (1). Search for structural, geomorphic, and chemical evidence of crustal recycling on Venus.
		AL. Atmospheric Losses (2). Quantify the processes by which the atmosphere of Venus loses mass to space, including interactions between magnetic fields and incident ions and electrons.
		MA. Magnetism (3). Characterize the distribution of any remanent magnetism in the crust of Venus.
	B. How does Venus elucidate possible pathways for planetary evolution in general?	
		CO. Core (2). Measure the size of the core of Venus and determine whether it remains partially liquid.

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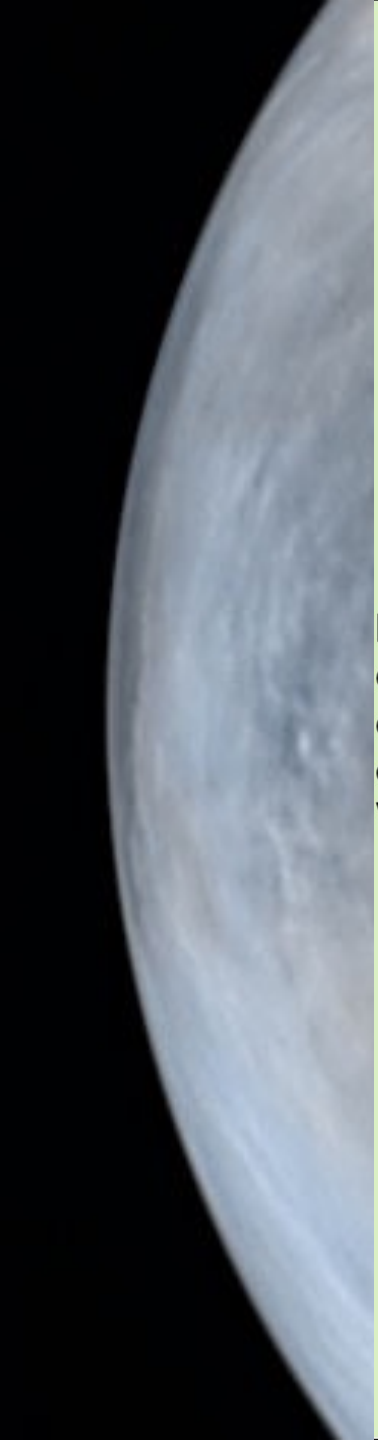
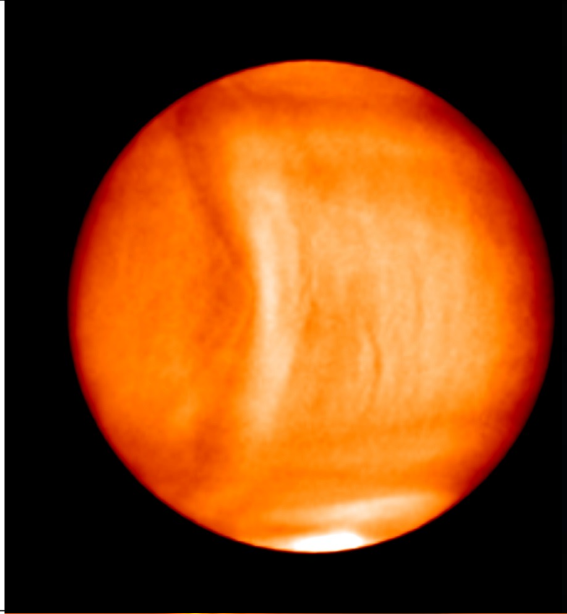
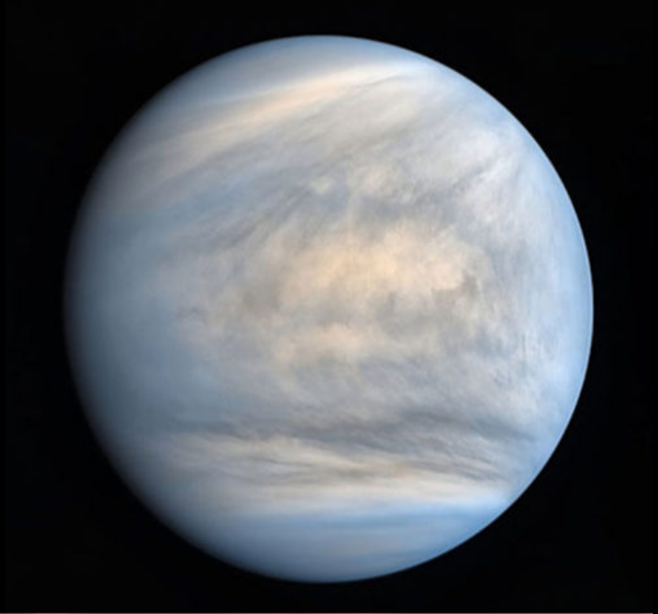
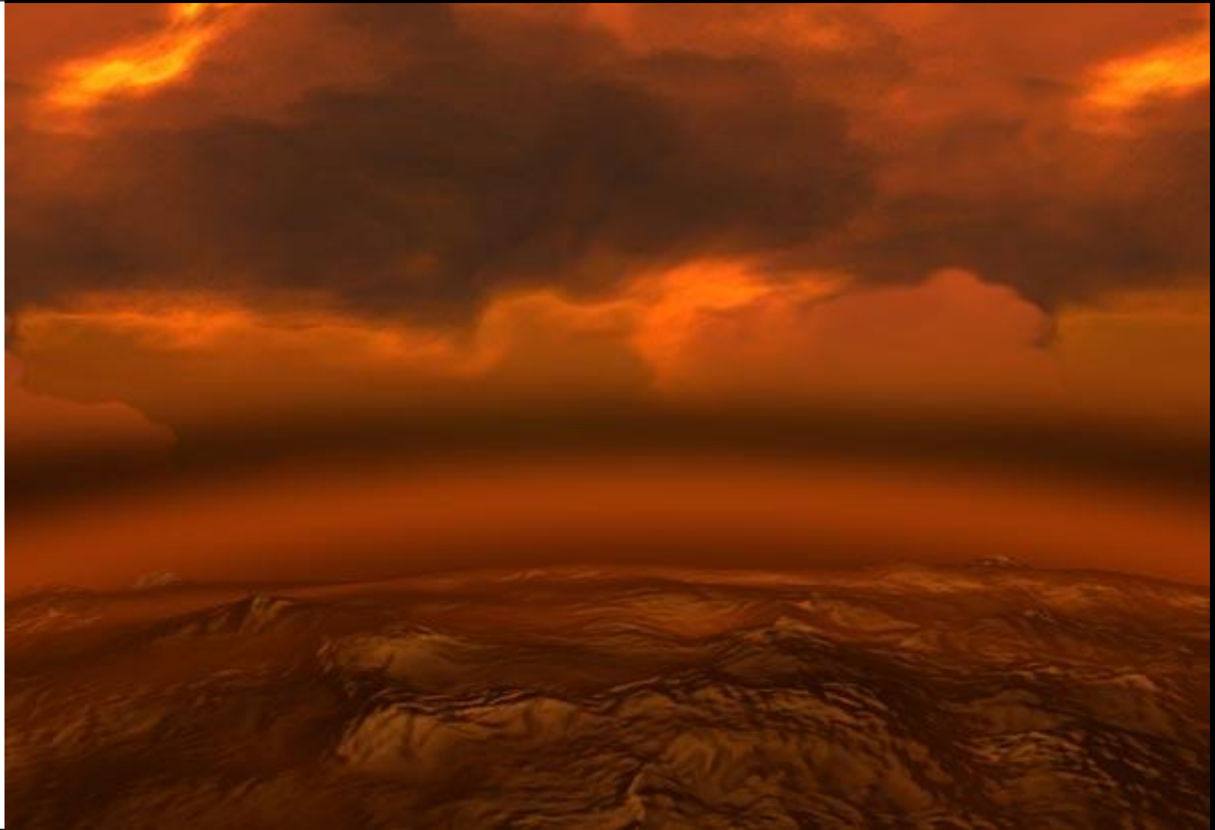
	B. How does Venus elucidate possible pathways for planetary evolution in general?	**IS. Isotopes (1).** Measure the isotopic ratios and abundances of D/H, noble gases, oxygen, nitrogen, and other elements in the atmosphere of Venus.
		LI. Lithosphere (1). Determine lithospheric parameters on Venus that are critical to rheology and potential geodynamic transitions, including: stress state, water content, physical structure, and elastic and mechanical thicknesses.
		HF. Heat flow (2). Determine the thermal structure of the lithosphere of Venus at present day and measure in situ heat flow.
		CO. Core (2). Measure the size of the core of Venus and determine whether it remains partially liquid.

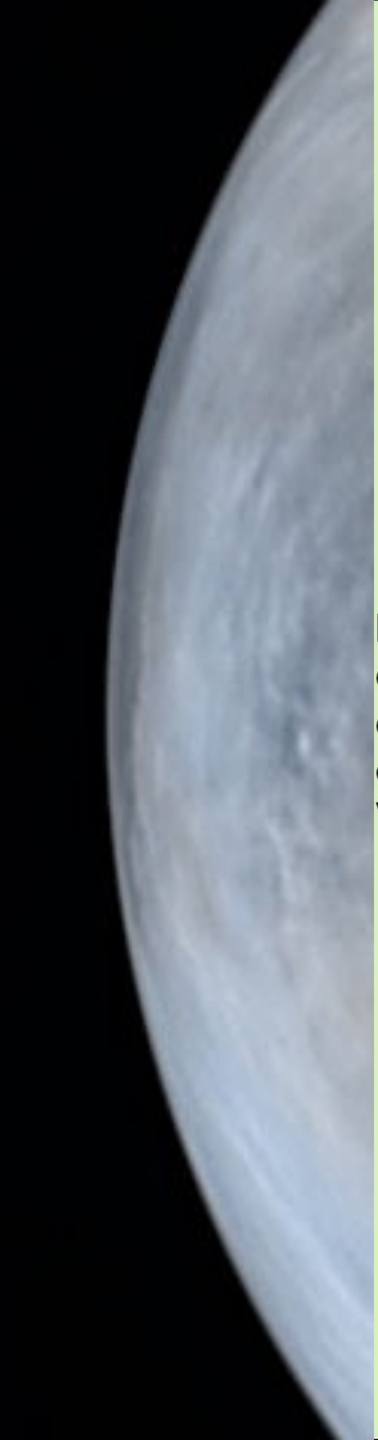


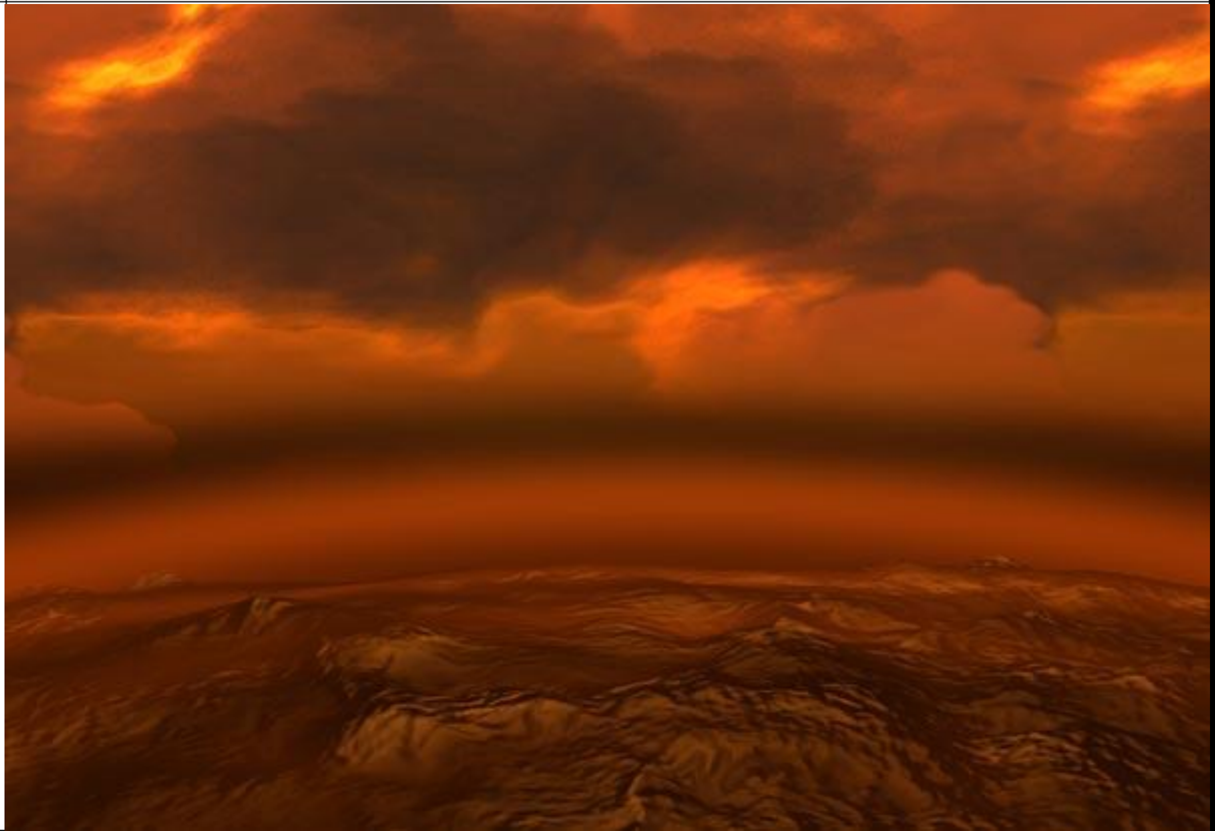
II. Understand atmospheric dynamics and composition on Venus.	A. What processes drive the global atmospheric dynamics of Venus?
	B. What processes determine the baseline and variations in Venus atmospheric composition and global and local radiative balance?

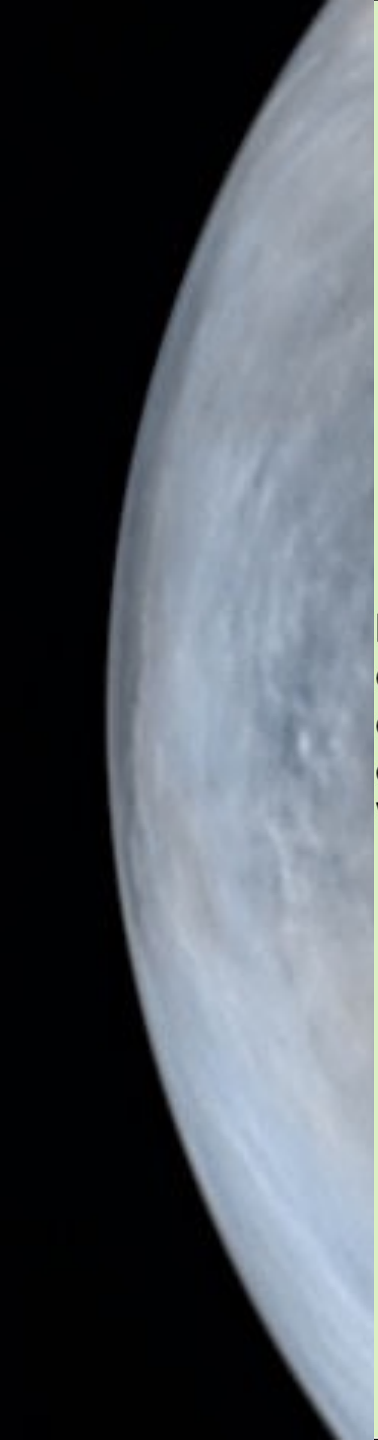








II. Understand atmospheric dynamics and composition on Venus.	A. What processes drive the global atmospheric dynamics of Venus?	**DD. Deep Dynamics (1).** Characterize the dynamics of the lower atmosphere (below about 75km) of Venus, including: retrograde zonal super-rotation, meridional circulation, radiative balances, mountain waves, and transfer of angular momentum.
		UD. Upper Dynamics (1). In the upper atmosphere and thermosphere of Venus, characterize global dynamics and interactions between space weather and the ionosphere and magnetosphere.
		MP. Mesoscale Processes (2). Determine the role of mesoscale dynamics in redistributing energy and momentum throughout the atmosphere of Venus.
	B. What processes determine the baseline and variations in Venus atmospheric composition and global and local radiative balance?	



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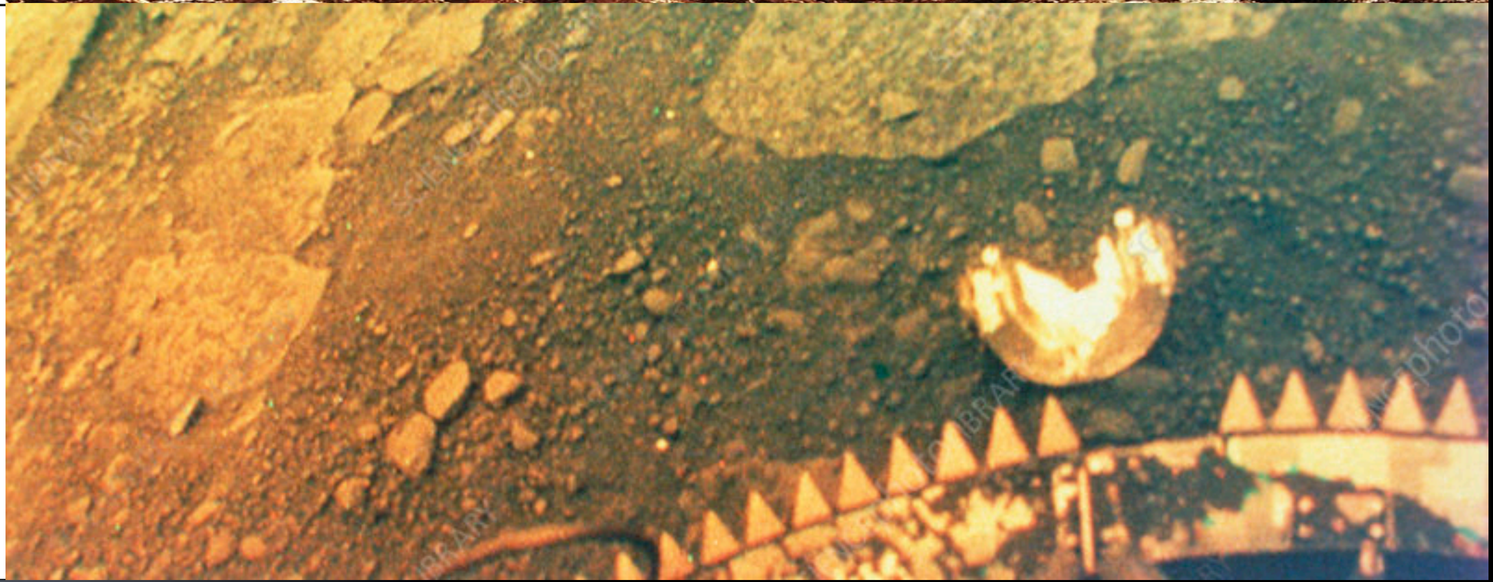
	B. What processes determine the baseline and variations in Venus atmospheric composition and global and local radiative balance?	**RB. Radiative Balance (1).** Characterize atmospheric radiative balance and how radiative transport drives atmospheric dynamics on Venus.
		IN. Interactions (1). Characterize the nature of the physical, chemical, and possible biological interactions among the constituents of the Venus atmosphere.
		AE. Aerosols (2). Determine the physical characteristics and chemical compositions of aerosols in Venus atmosphere as they vary with elevation, including discrimination of aerosol types/components.
		UA. Unknown Absorber (2). Characterize the unknown short-wavelength absorber in the upper atmosphere of Venus and its influence on local and global processes.
		OG. Outgassing (3). Determine the products of volcanic outgassing on Venus and their effects on atmospheric composition.

<table>
<tr><td rowspan="2">III. Understand the geologic history preserved on the surface of Venus and the present-day couplings between the surface and atmosphere.</td><td>A. What geologic processes have shaped the surface of Venus?</td><td></td></tr>
<tr><td>B. How do the atmosphere and surface of Venus interact?</td><td></td></tr>
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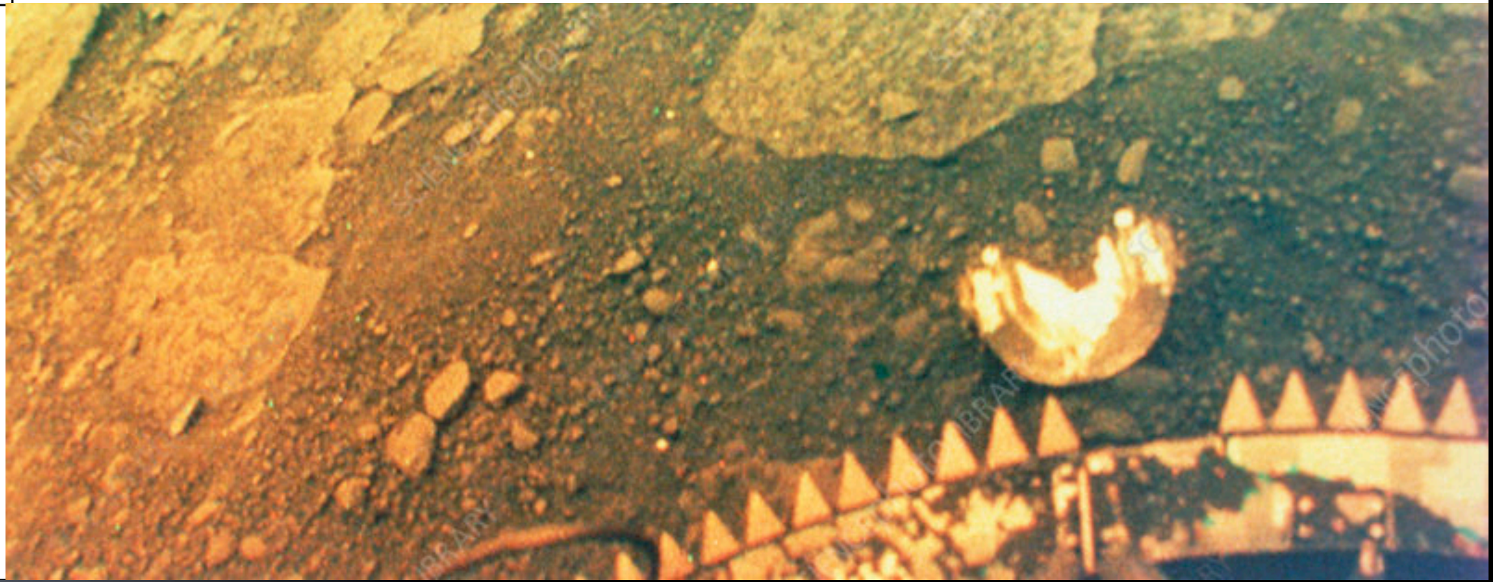
III. Understand the geologic history preserved on the surface of Venus and the present-day couplings between the surface and atmosphere.	A. What geologic processes have shaped the surface of Venus?	**GH. Geologic History (1).** Develop a geologic history for Venus by characterizing the stratigraphy, modification state, and relative ages of surface units.
		GC. Geochemistry (1). Determine elemental chemistry, mineralogy, and rock types at localities representative of global geologic units on Venus.
		GA. Geologic Activity (1). Characterize current volcanic, tectonic, and sedimentary activity that modifies geologic units and impact craters and ejecta on Venus.
		CR. Crust (2). Determine the structure of the crust of Venus in three dimensions and thickness across the surface.
	B. How do the atmosphere and surface of Venus interact?	



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<tr><td>GW. Global Weathering (2). Determine the causes and spatial extents of global weathering regimes on Venus.</td></tr>
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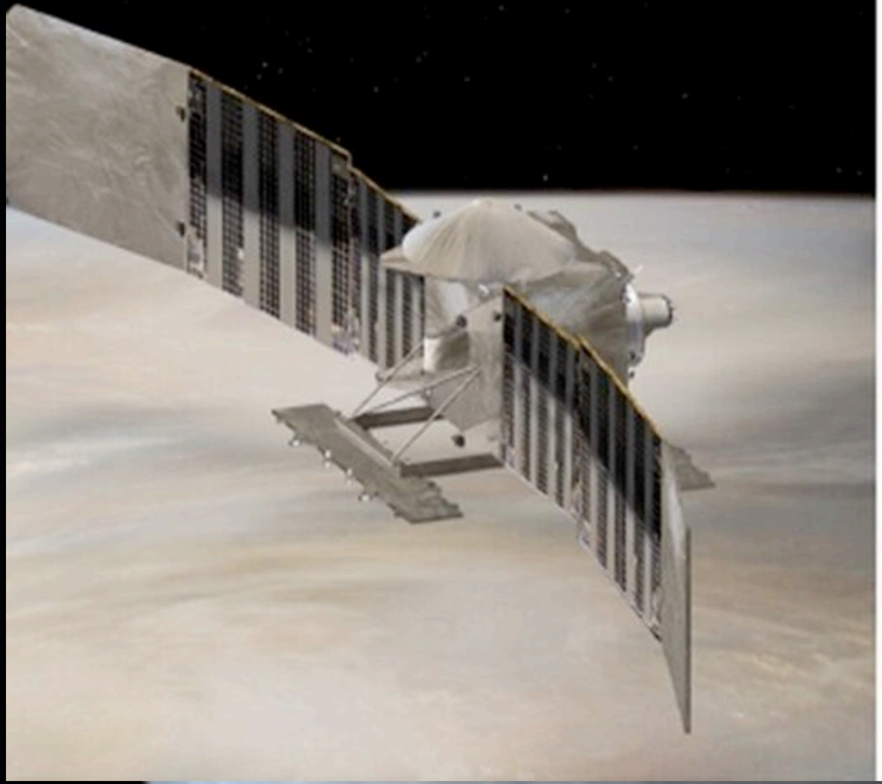
</table>

Redefining the Obtainable
V3NUS = VERITAS, DAVINCI, EnVision



VERITAS

DAVINCI

ENVISION

Understanding why our closest neighbour is so different

Redefining the Obtainable
V3NUS = VERITAS, DAVINCI, EnVision

Dark Green - "Substantially Addressed"

The Investigation would need to be substantially incremented/revised after V3NUS completion.

Medium Green – "Partially Addressed"

The Investigation might need to be incremented/revised after V3NUS completion.

Light Green – "First Look"

The Investigation could be incremented/revised after V3NUS completion.

White – "Not substantially addressed"

The V3NUS missions won't affect these Investigations.

Goal	Objective	Investigation	Achieved by end of V3NUS	Future Achievement
I. Understand Venus' early evolution and potential habitability to constrain the evolution of Venus-size (exo)planets.	A. Did Venus have temperate surface conditions and liquid water at early times?	**HO. Hydrous Origins**	Near-IR emissivity maps, searching for widespread felsic crust.	**Measurement of surface rock composition in situ (e.g. XRF, GRS, LIBS), particularly in tesserae**
		RE. Recycling	Radar maps, subsurface sounding, Near-IR emissivity maps.	**Measurement of surface rock composition in situ (e.g. XRF, GRS, LIBS).** Follow-up high-res radar & high res NIR surface imaging
		AL. Atmospheric Losses	-	Orbital measurements of ionosphere & solar wind interaction; sub-mm sounder to measure winds and transport through lower thermosphere
		MA. Magnetism	-	**Magnetic fields** measured from orbit **and/or balloon**
	B. How does Venus elucidate possible pathways for planetary evolution in general?	**IS. Isotopes**	Comprehensively addressed by DAVINCI+.	**Next generation MS instruments on long-lived cloud platform** may be able to achieve even higher sensitivity
		LI. Lithosphere	Comprehensively addressed by VERITAS & EnVision's SAR & gravity.	Seismometry; Magnetotelluric sounding; **In situ measurements of surface material composition**. Follow-up high-res radar & high res NIR surface imaging
		HF. Heat flow	Constraints from gravity/ topography calcs; also from detection & characterization of volcanism & tectonism.	***Seismometry***; in situ heat flow
		CO. Core	Strongly constrained by gravity measurements & spin vector variation monitoring.	***Seismometry*. Higher accuracy gravity. Magnetic field measurements from orbit and/or aerobot**

Goal	Objective	Investigation	Achieved by end of V3NUS	Future Achievement
II. Understand atmospheric dynamics and composition on Venus.	A. What processes drive the global atmospheric dynamics of Venus?	**DD. Deep Dynamics**	Vertical profile of P, T, wind, from DAVINCI; cloud-level winds & waves from cloud tracking particularly from Akatsuki; gas mapping & radio occultation from EnVision; surface winds from Aeolian features from SAR.	**Cloud-level 3-D winds & waves from aerobot.** Long-life surface meteorological station. Next-generation cloud tracking from orbit. Sat-to-Sat radio occultations for frequent T profiles at 40 – 90 km
		UD. Upper Dynamics	-	Ionosphere / magnetosphere / plasma / solar wind interaction orbital measurements. Sub-mm heterodyne to measure winds & transport at 70 – 140 km, or thermal IR sounding of mesosphere (60 – 100 km)
		MP. Mesoscale Processes	Constraints on winds & waves from Akatsuki & Envision. VERITAS, DAVINCI camera elements.	**Cloud-level 3-D winds & waves from aerobot. Simultaneous orbital & in situ atmospheric observations.** Long-life meteorological station
	B. What processes determine the baseline and variations in Venus atmospheric composition and global and local radiative balance?	**RB. Radiative Balance**	Radiative flux measurement from DAVINCI+ descent probe. New spectroscopy from orbit by EnVision.	Radiative flux measurements from descent probe. **Cloud-level radiative flux measurements from aerobot**. Long-life radiometric/meteorological station
		IN. Interactions	DAVINCI+ chemical profiles, and EnVision's maps of key volatile gases, and links to volcanic activity as studied by VERITAS & EnVision.	**In situ characterization of cloud particles, radiation, microphysics. Search for lighting** (**aerobot**, orbiter). Aeolian processes (lander, orbiter)
		AE. Aerosols	VERITAS/VEM, and EnVision/VenSpec will map aerosol distributions. DAVINCI+ will measure the gaseous volatile species which participate in condensational cloud formation.	**In situ cloud-level aerobot measuring cloud and gas composition, and particle size & shape. Characterization of dust at surface**
		UA. Unknown Absorber	VenSpec-U and CUVIS will contribute new UV observations. DAVINCI contributes to understanding of chemical inventory in clouds.	**In situ cloud-level aerobot measuring cloud, gas, aerosol composition, especially at altitudes > 60 km, and UV/blue fluxes**
		OG. Outgassing	DAVINCI+ will obtain a vertical profile of composition including volcanically outgassed volatiles; EnVision-VenSpec will map major outgassed volatile species.	**In situ measurements of surface and cloud materials to search for signatures of outgassed volatiles**

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III. Understand the geologic history preserved on the surface of Venus and the present-day couplings between the surface and atmosphere	A. What geologic processes have shaped the surface of Venus?	**GH. Geologic History**	global SAR imaging & topography, nIR emissivity, gravity & subsurface mapping including high-res imaging follow-up.	**In situ measurement of surface composition (multiple locations?)**. Follow-up high-res radar & **high res NIR surface imaging**
		GC. Geochemistry	Constraints from nIR emissivity maps (& SAR & radiometry).	**In situ measurement of surface composition**
		GA. Geologic Activity	Change detection in repeated SAR imagery [with limited repeat-pass InSAR for cm-scale changes], nIR & RF thermal anomaly search, volcanic plume search (EnVision), volcanic tracer search (DAVINCI).	Systematic surface monitoring with repeat-pass InSAR & radiometry (NIR & RF). Seismometry (surface aerobot, or orbital)
		CR. Crust	Addressed by VERITAS & EnVision's SAR & gravity, and EnVision's Sub-surface sounding, and DAVINCI descent imaging.	***Seismometry***; Magnetotelluric sounding; **In situ measurements of surface material composition.**
	B. How do the atmosphere and surface of Venus interact?	**LW. Local Weathering**	Constraints from nIR emissivity maps (& SAR & radiometry) *[but see text – this really targets lander measurements]*. Also DAVINCI measurements of near-surface atmospheric composition.	**In situ measurement of surface & atmosphere composition (at multiple localities)**
		GW. Global Weathering	Constraints from nIR emissivity maps (& SAR & radiometry) & SAR imagery.	**In situ measurement of surface & atmosphere composition, global patterns**
		CI. Chemical Interactions	DAVINCI measurements of near-surface atmospheric composition. EnVision measurements of tropospheric gas abundances. VERITAS & EnVision maps of clouds & low-altitude water vapour. Study of radar anomaly.	Surface landers & meteorological stations. Follow-up high res radar and other surface mapping

Next Gen Venus

Ionosphere / escape orbiters

"VAVEN", VFM smallsats

Atmospheric remote sensing orbiters

HOVER, VESPER

Next-gen geophysics orbiters

High-res 1-m class imaging SAR

Cloud-level aerobots

VFM aerobot, VALOR, Aereal Laboratory

Lander

VFM lander, Venera-D lander

Long-lived surface station

LLISSE, SAEVe, weather/seismic network(s)

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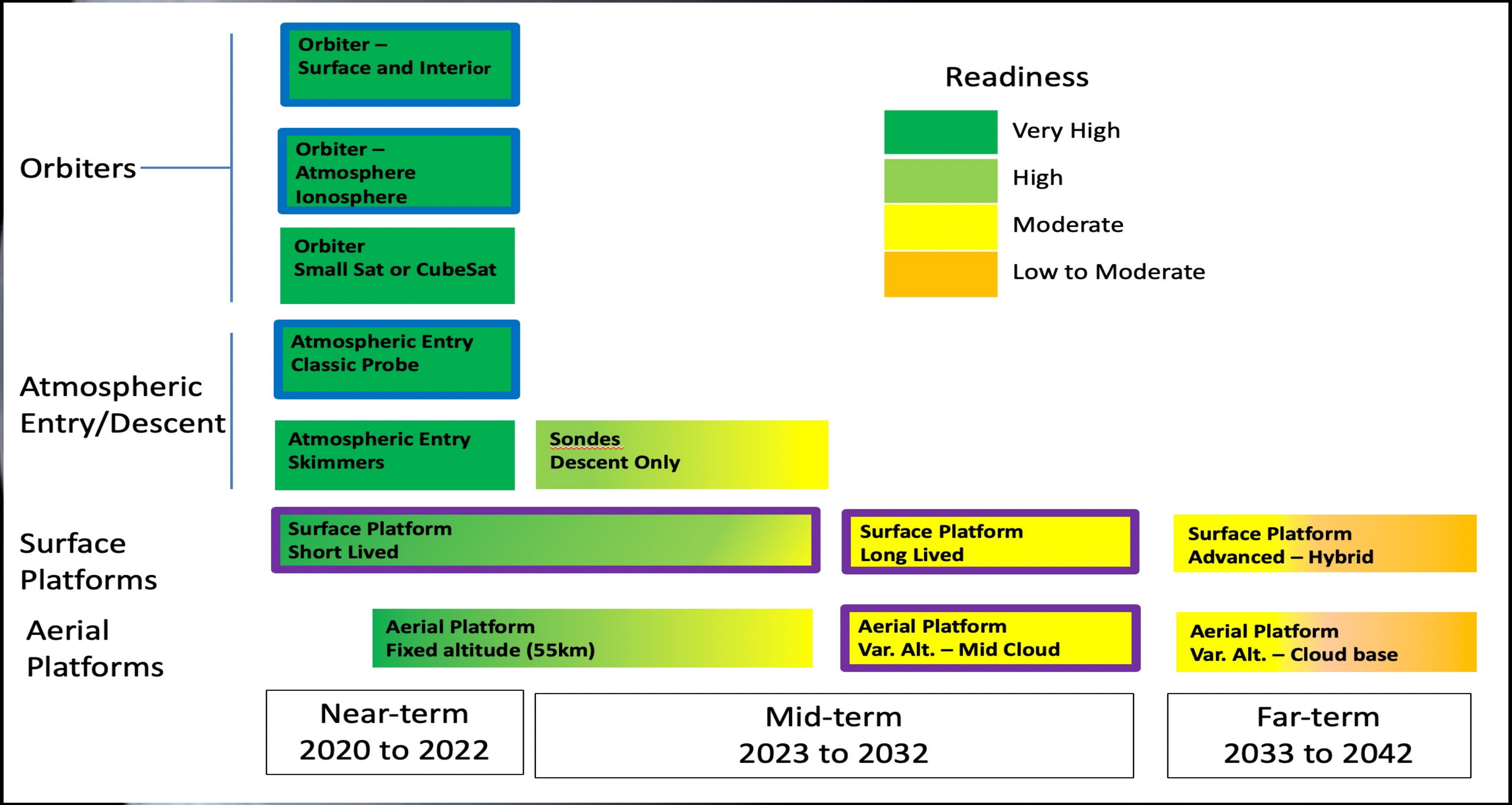
Sample Retrieval?

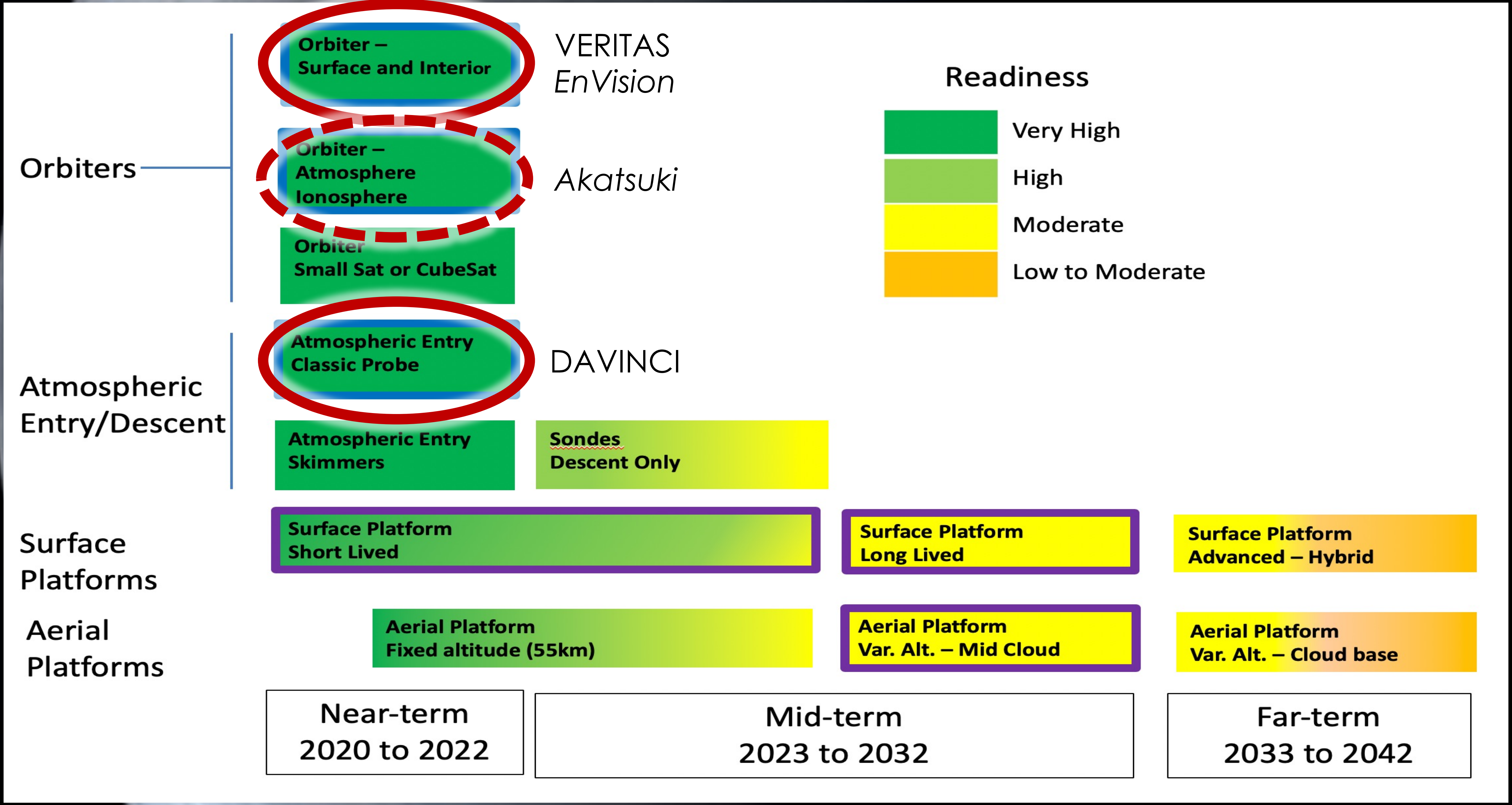
What is considered a "feasible" architecture by VEXAG currently?

- All elements of the GOI were considered technically feasible to one level or another during the period of the next decadal
- Many Investigations need technical advances for complete answers
- The next talks will all bound what is and will be technically feasible today and in the coming years
- Technical vs. programmatic feasibility -> Readiness -> Venus Roadmap and Technology Plan

Venus Roadmap



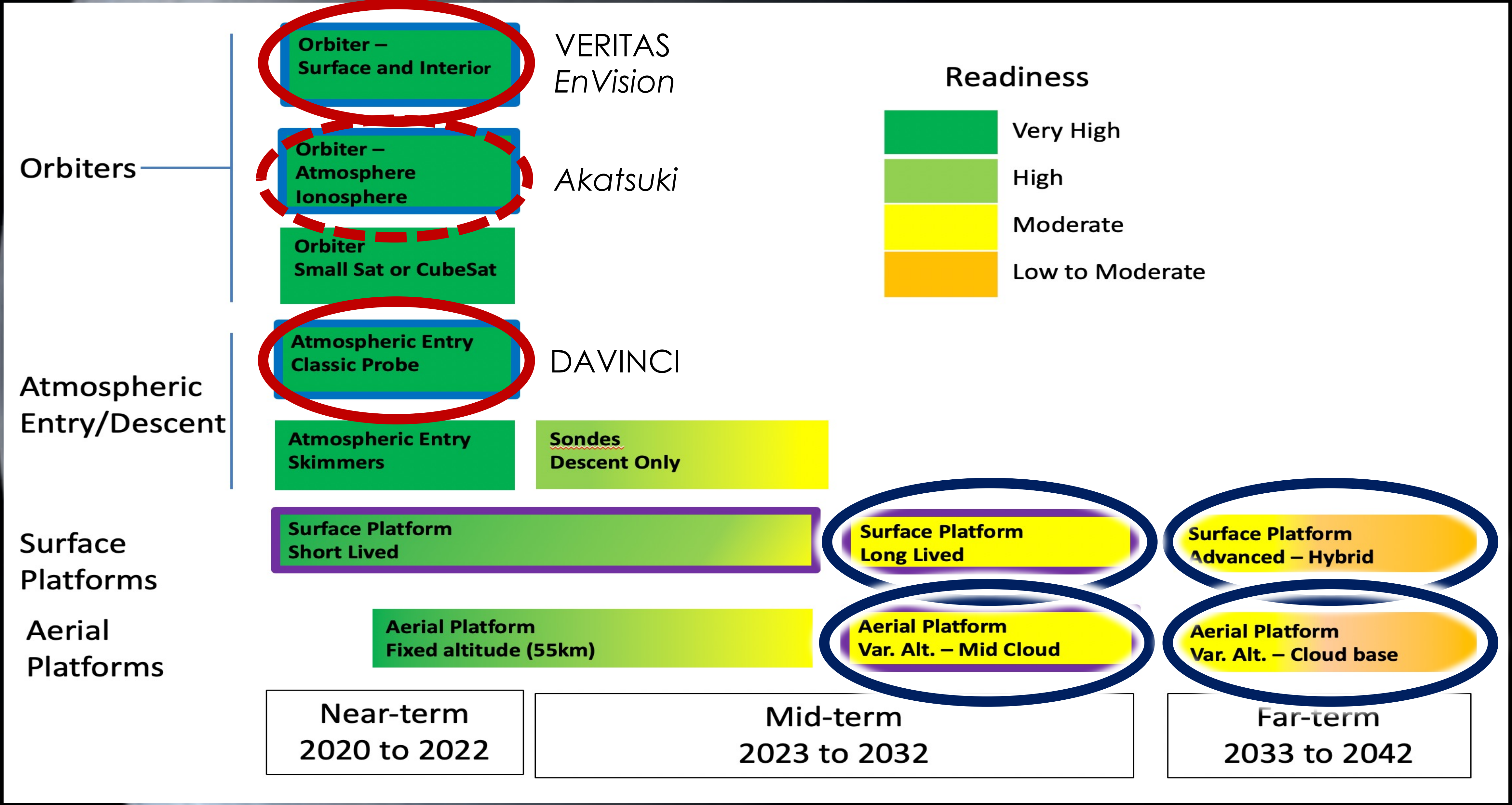
Venus Roadmap



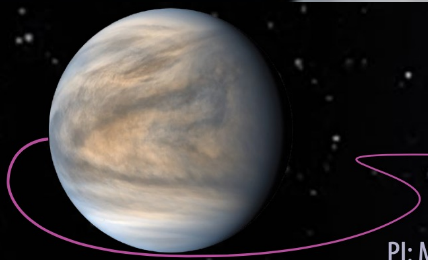
Which of the questions are not directly addressed with "Feasible" architectures?

- In Situ Heat Flow - Drilling below 1 m, multiple locations
- Definitive surface, elemental, mineral composition
- Global Internal Structure, Activity - Seismic networks
- Volcanic Rates - monitoring networks
- Diurnal/Annual Patterns deep atmosphere/surface

Venus Roadmap



FACT SHEET



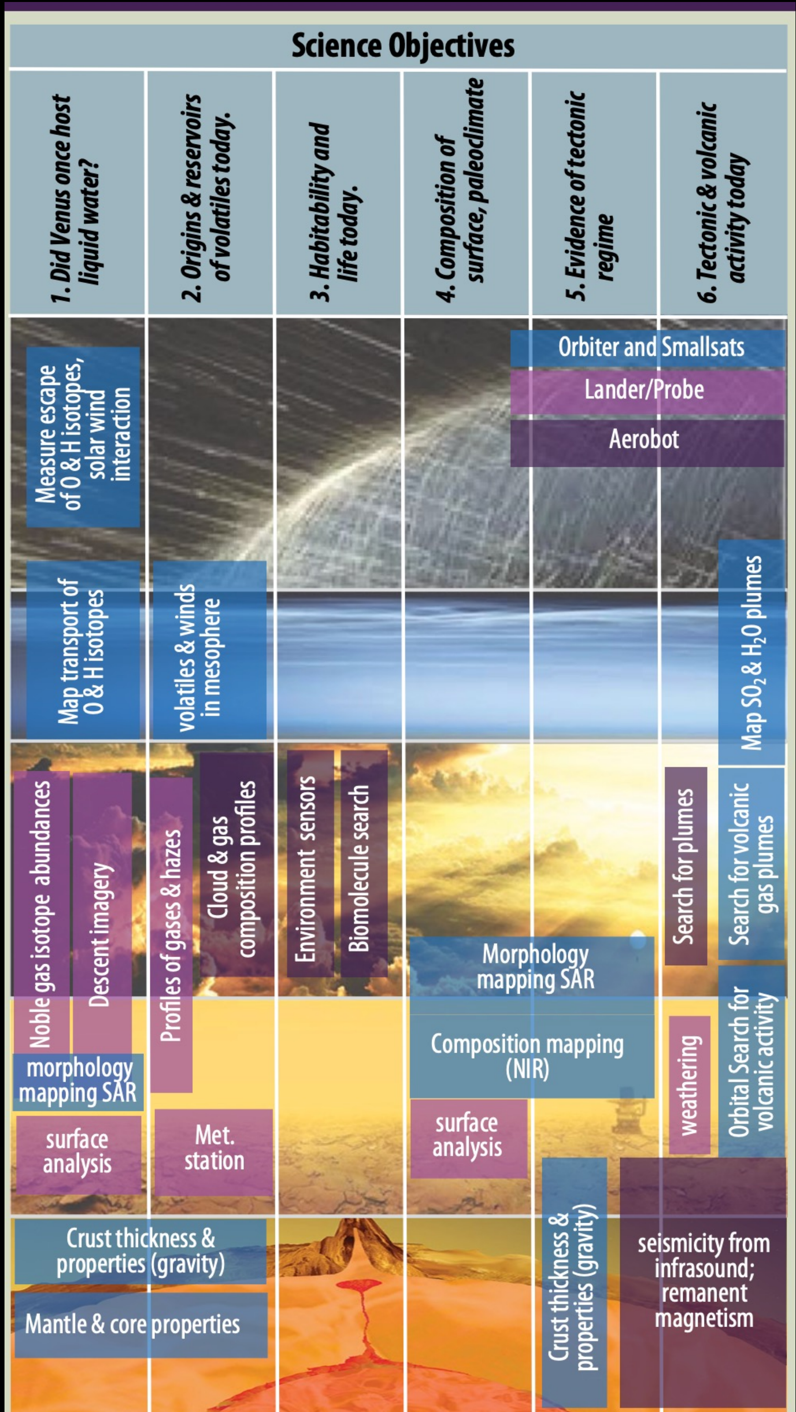
Venus Flagship Mission Study

A MISSION TO EXPLORE THE HABITABILITY OF VENUS

PI: Martha Gilmore, *Wesleyan University*; D-PI: Patricia Beauchamp, *Jet Propulsion Laboratory, California Institute of Technology*

Processes to be Studied	Altitude Ranges (approximate)
Escape to space	Exosphere 200 km
Photodissociation to H^+, OH^-, O^+	Thermosphere 100 km
H_2O & SO_x cycles in mesosphere	Mesosphere 70 km
Volatile cycling in the clouds	Cloud Layers 50 km
Thermochemistry in troposphere	Troposphere
Weathering Active volcanism? Tectonism?	Surface 0 km Crust
Volatile cycling in Crust, Mantle and Core	-50 km Mantle, Core -6050 km

VN024



What questions that are NOT called out in VEXAG that we would be asking if we thought we could?

- Deep Structure
- Absolute Age
- Global Compositional Variety

Deep Structure

Study of Earth over decades reveals a heterogeneous deep structure.

Mantle plumes, laterally varying depths of seismic velocity discontinuities associated with mantle phase transitions, large low shear velocity provinces, and ultra-low velocity zones in the mantle (e.g., French and Romanowicz 2015; Hernlund and McNamara 2015 and many more).

This structure reflects thermal and/or compositional variations that constrain planetary accretion, differentiation, and ongoing processes (e.g. True Polar Wander, mantle convection, volcanic plumes, etc

Absolute Ages

In the absolute sense, nothing is known about the surface age of rocks on Venus' surface.

Impact ages suggest the surface may be quite young (McKinnon et al. 1997)

Some units might date from a time when Venus was habitable (Gilmore et al. 2017; Hansen and Lopez 2010).

Technology for in situ age dating is rapidly evolving

A long-term goal of the Venus Exploration Program is to obtain analogous in situ measurements of multiple locations on the surface.

SAM, LIBS, Retrieval

Global Compositional Variety

Detailed elemental, mineralogical compositions and atmosphere-surface processes at multiple different locations across the planet

This is a “mixed” problem – we know how to do this at point locations feasibly (depth/age problem)

How do we get to multiple locations feasibly?

- Autonomy
- Roving
- Sample retrieval

What are the atmospheric/temperature environmental conditions that can be challenges/benefits for returning to upper atmosphere?

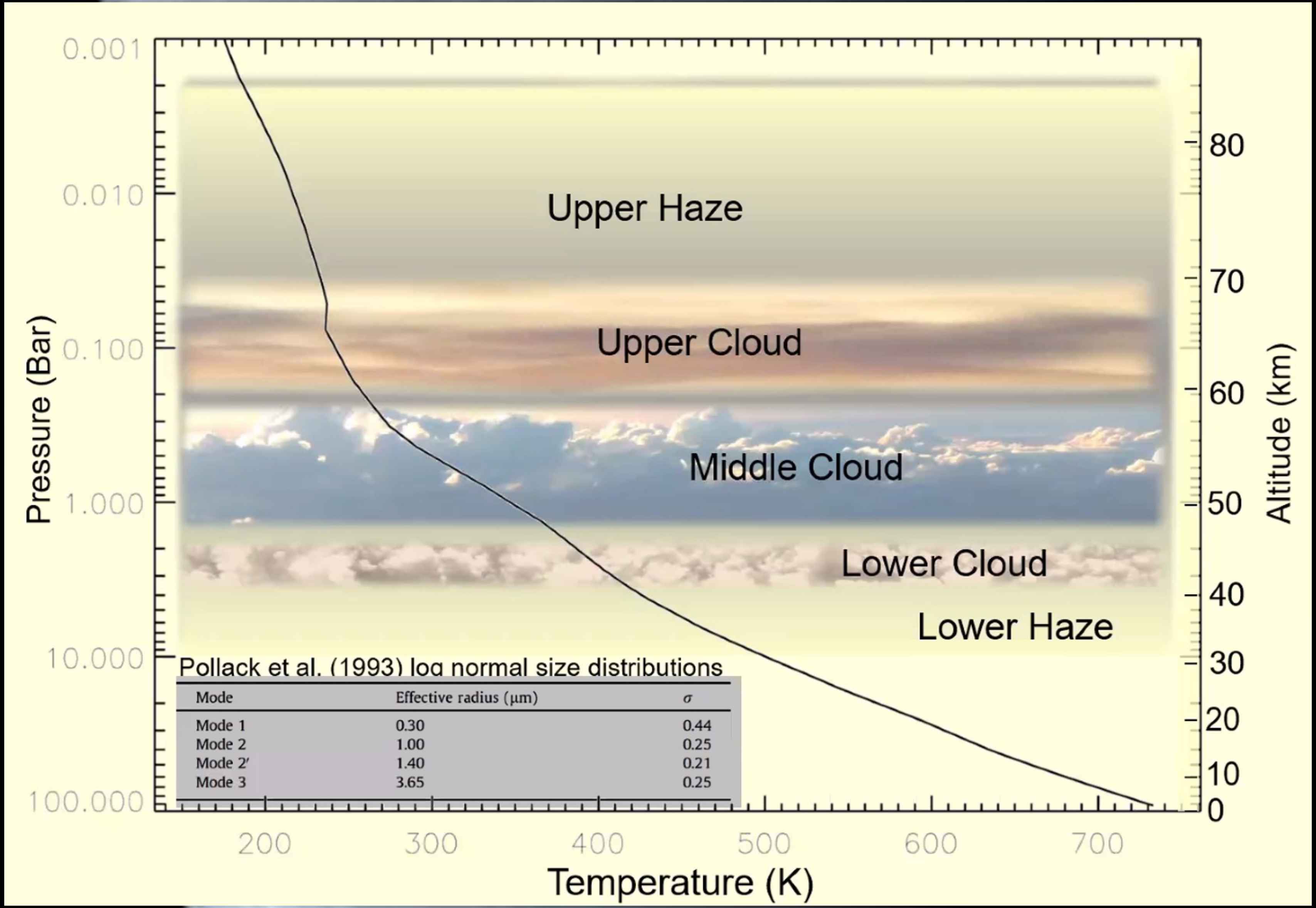
465 °C

95 Bar of mostly CO_2

Sulfuric Acid clouds

To start

Cloudy Venus

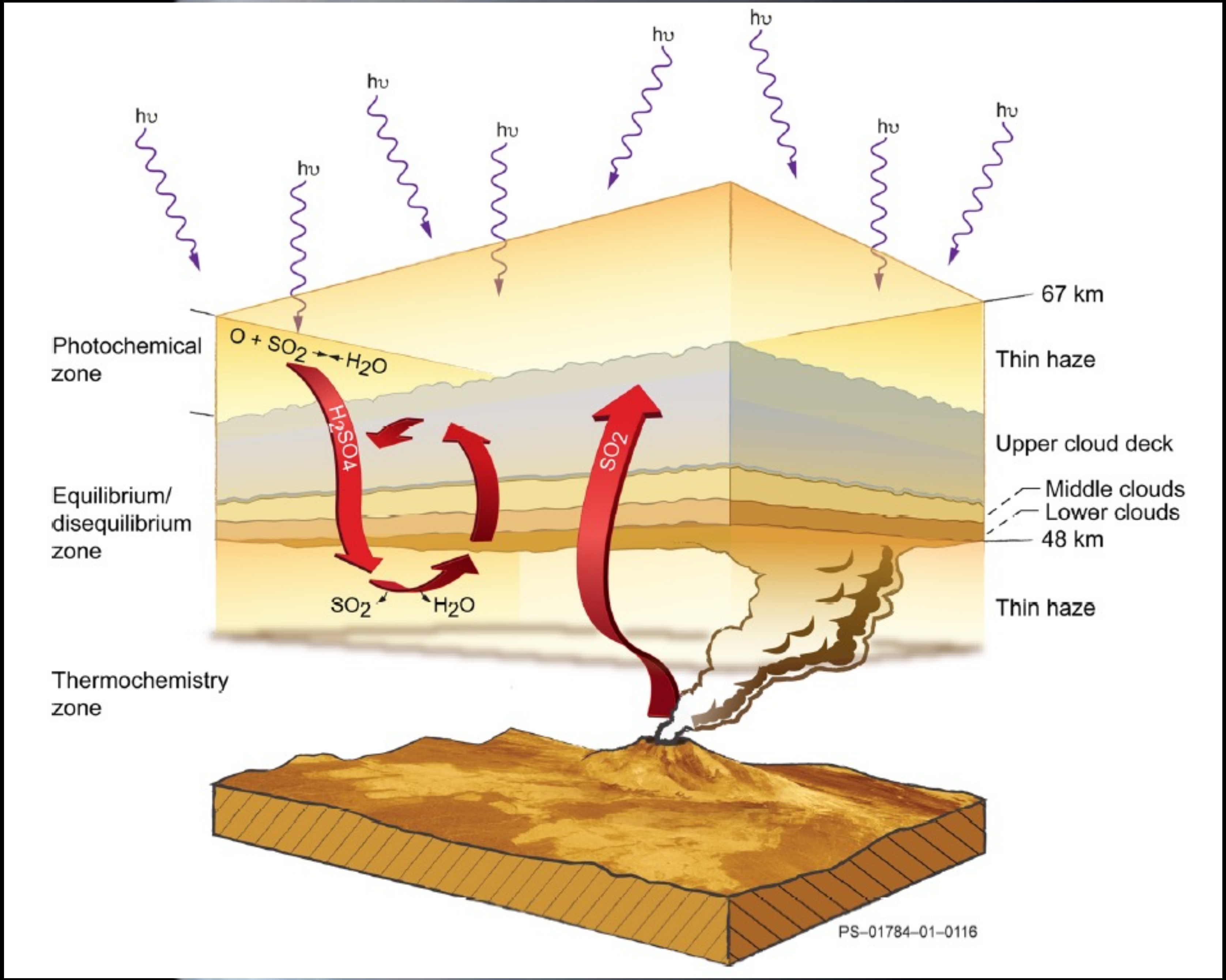


Multiple cloud and haze layers

Clouds are primarily (75-85%) sulfuric acid droplets

David Crisp

Atmosphere



Atmosphere:

- CO_2: 96.5 ± 0.8%
- N_2: 3.5 ± 0.8%
- SO_2: 150 ± 30 ppmv
- H_2O: 30 ± 15 ppmv
- CO: 17 ± 1.4 ppmv
- OCS: 4.4 ±1 ppmv
- H_2S: 3 ± 2 ppmv
- HCl: 0.4 ± 0.03 ppmv
- HF: 5 ± 3 ppbv

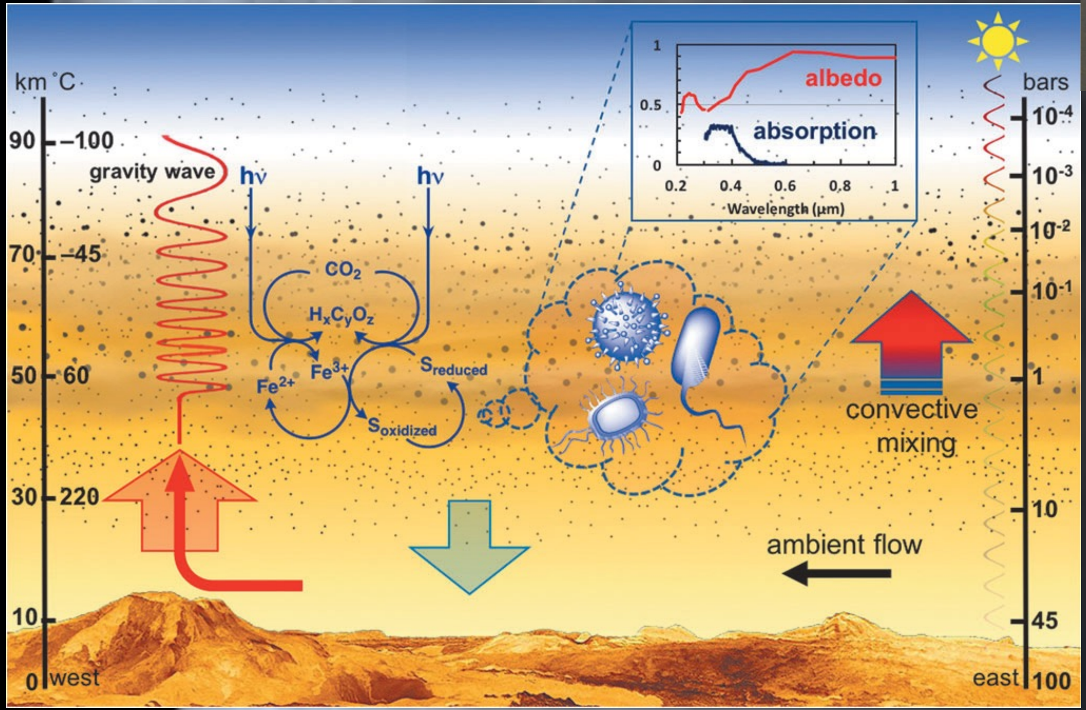
Giada Arney

Letter

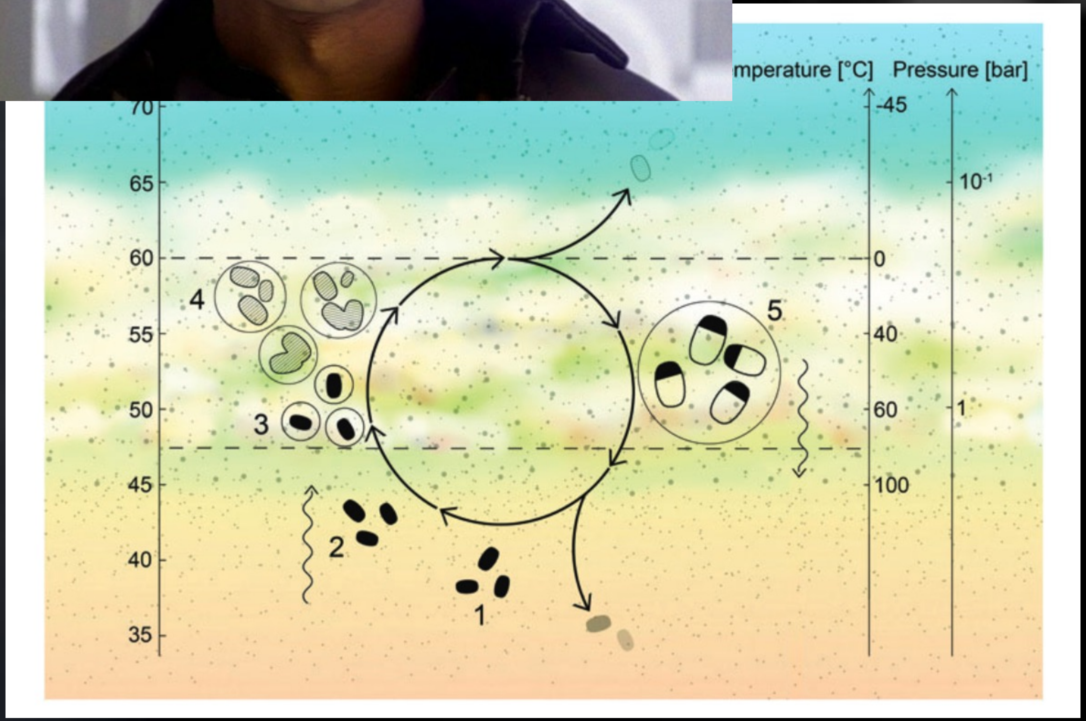
Life in the Clouds of Venus?

HAROLD MOROWITZ & CARL SAGAN

Nature **215**, 1259–1260 (16 September 1967)
doi:10.1038/2151259a0
Received: 04 August 1967
Published: 16 September 1967

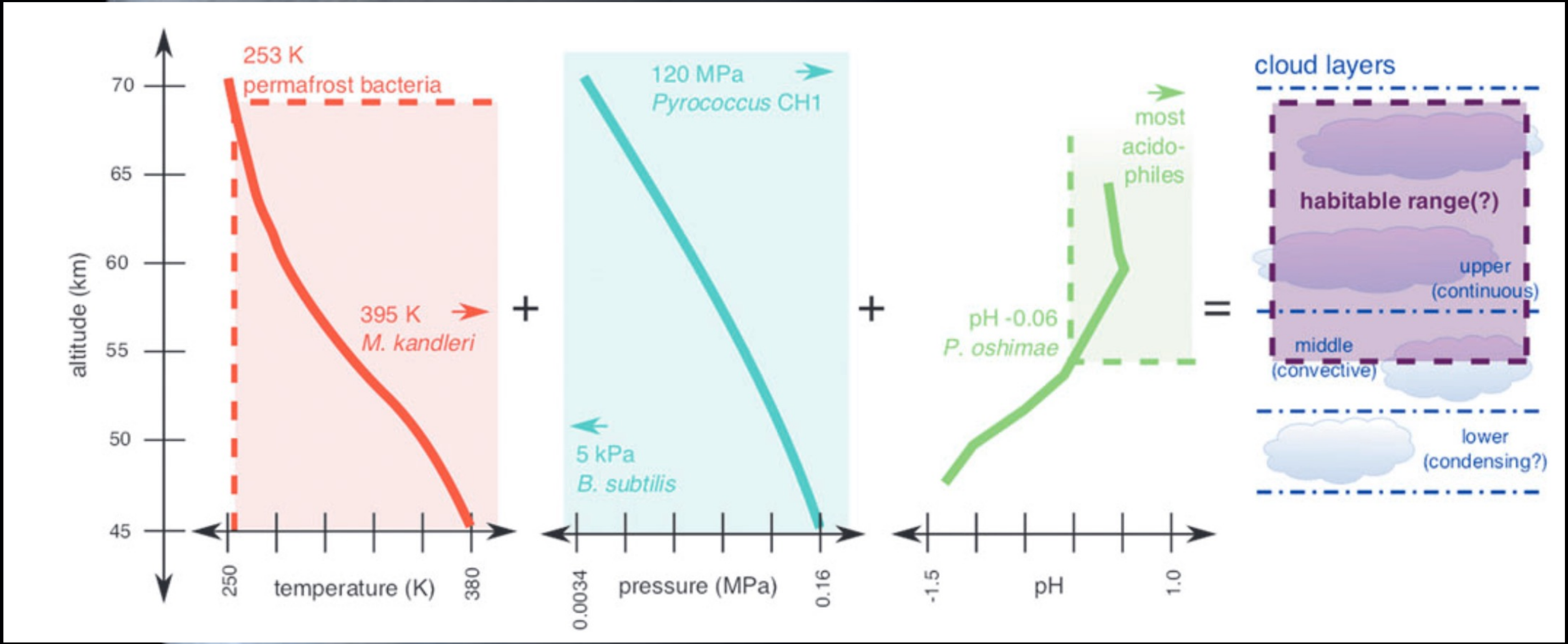


Limaye et al., 2018



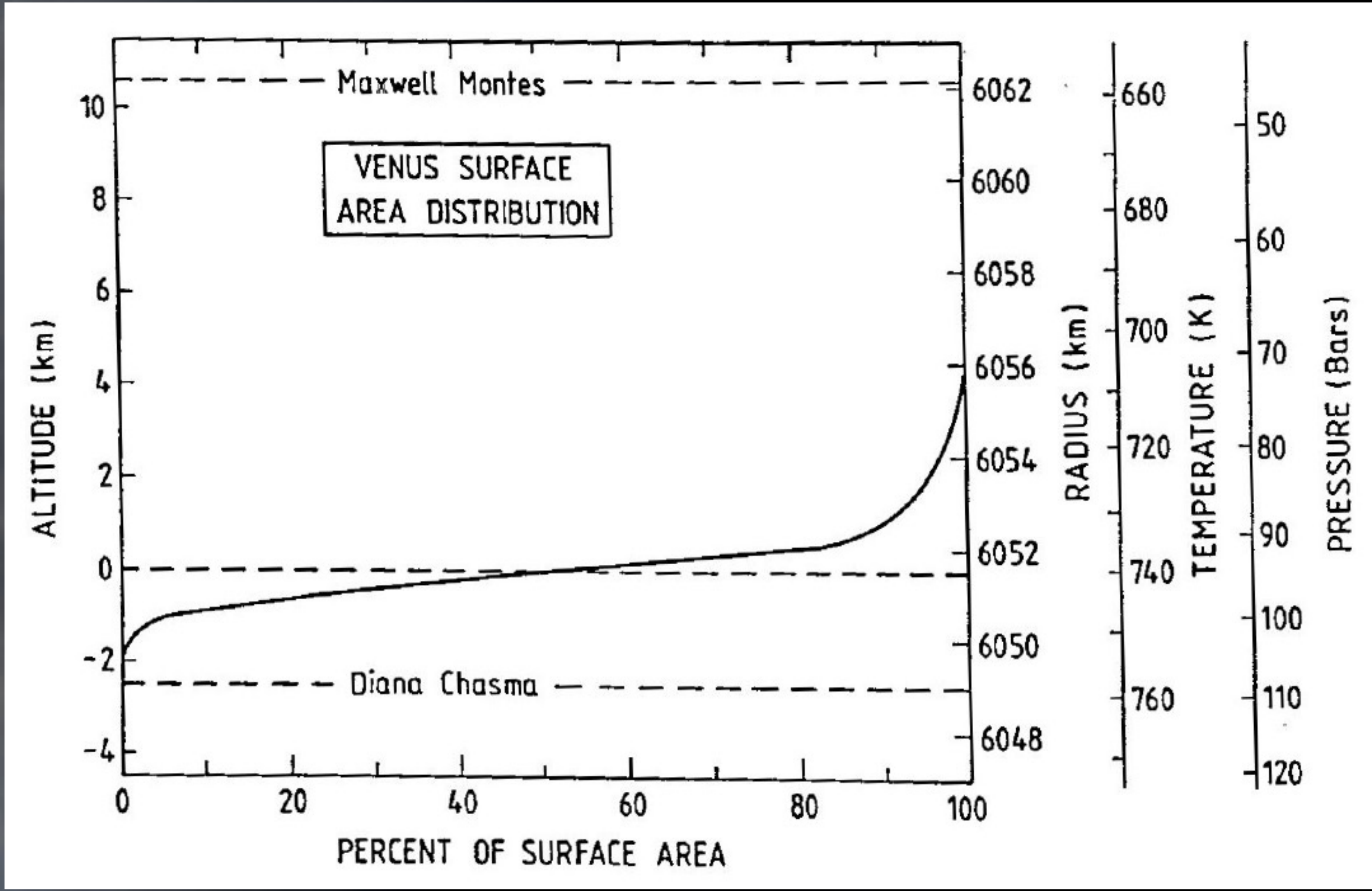
Seager et al., 2021

Habitability in Venus Atmosphere



Arriving in and Escaping the Heat

- Fast descents to the surface will still take most of an hour
- Ascent to more temperate climates is not instantaneous
- Time above 200-300 °C on the order of 1 hour may (?) be unavoidable

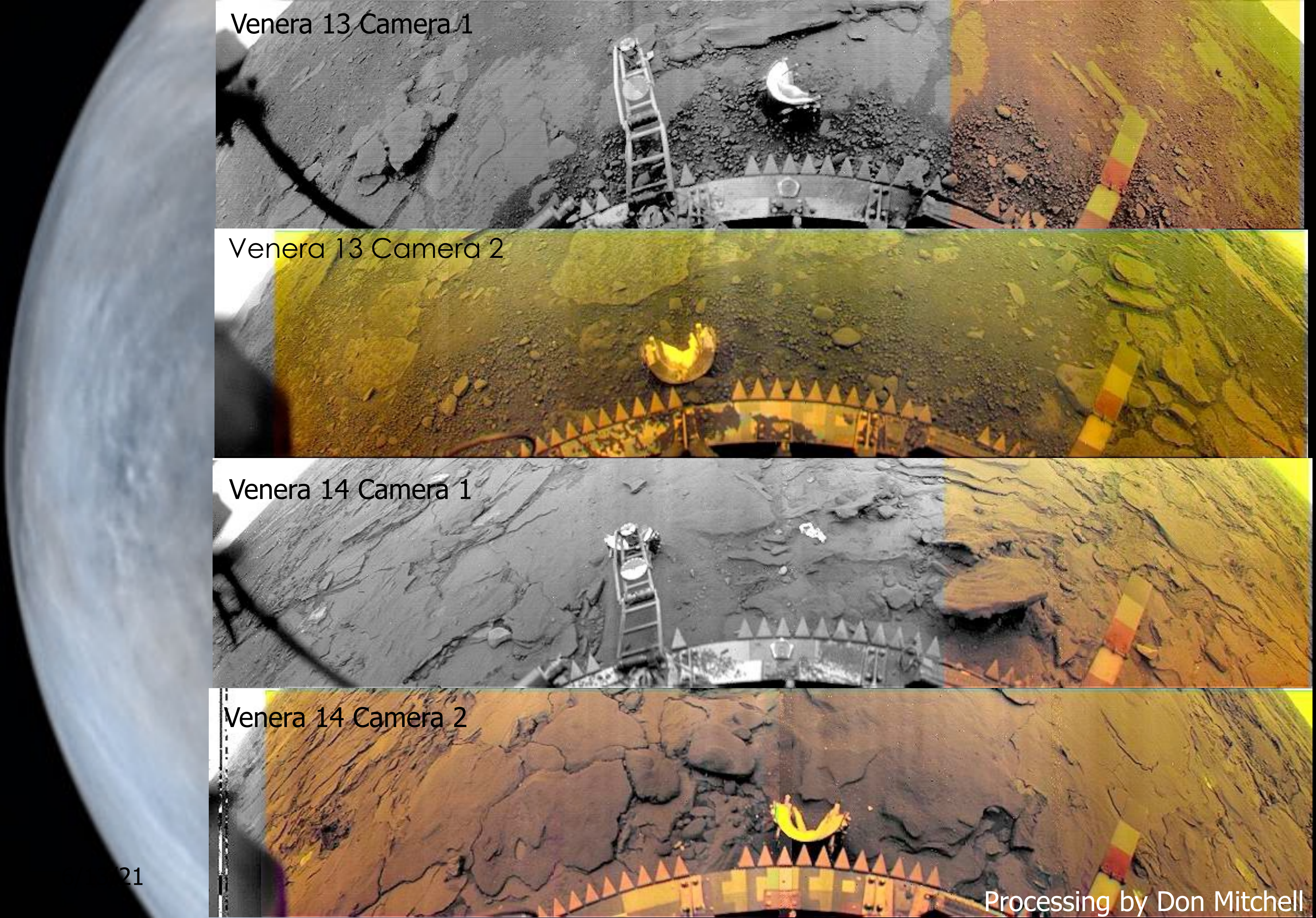


(Fegley and Treiman, 1992)

Surface Roughness at Lander Scale

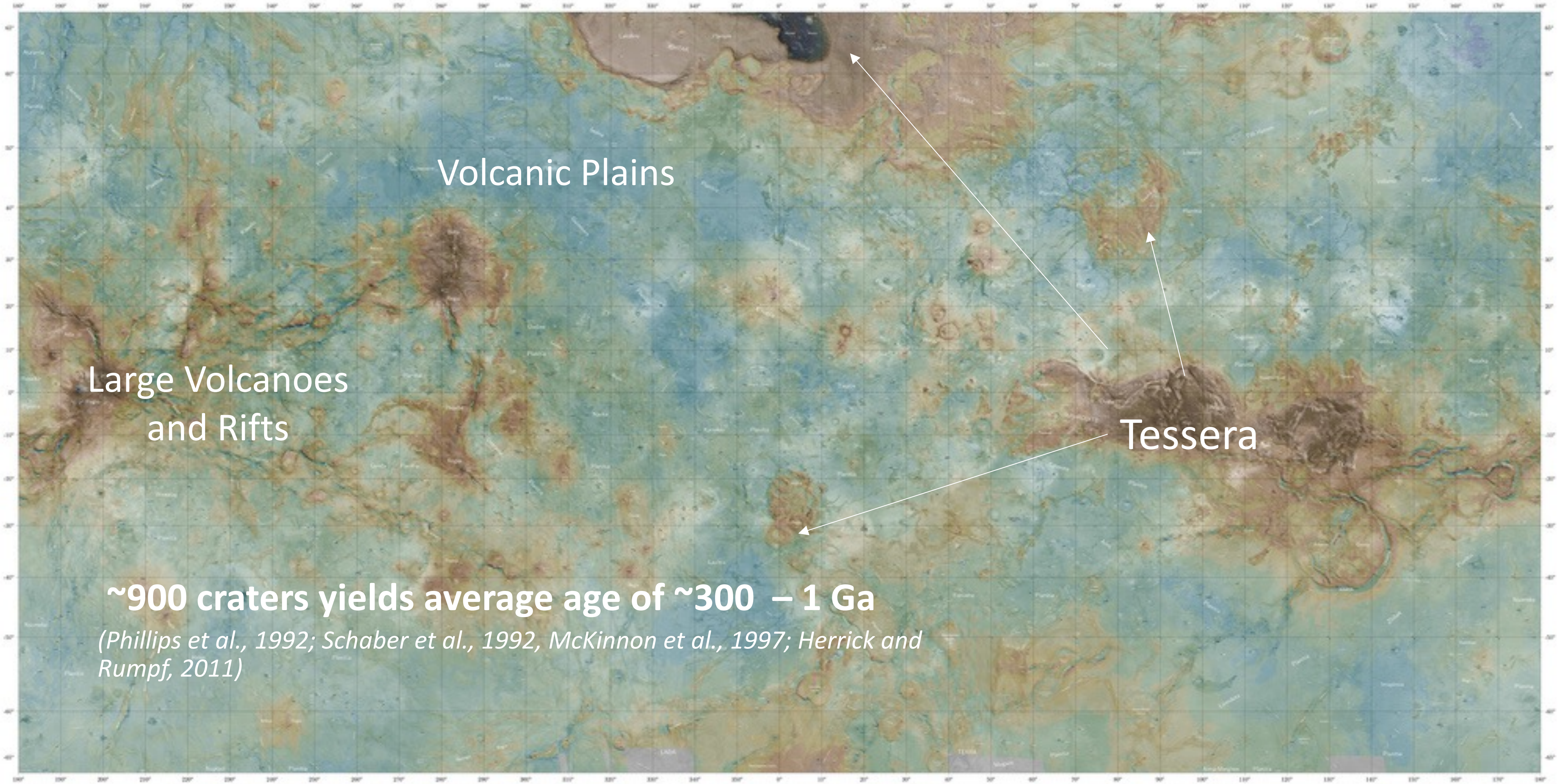
Venera 9 Panorama

Venera 13


Venera 13 Camera 1
Venera 13 Camera 2
Venera 14 Camera 1
Venera 14 Camera 2
Processing by Don Mitchell

Lada Region

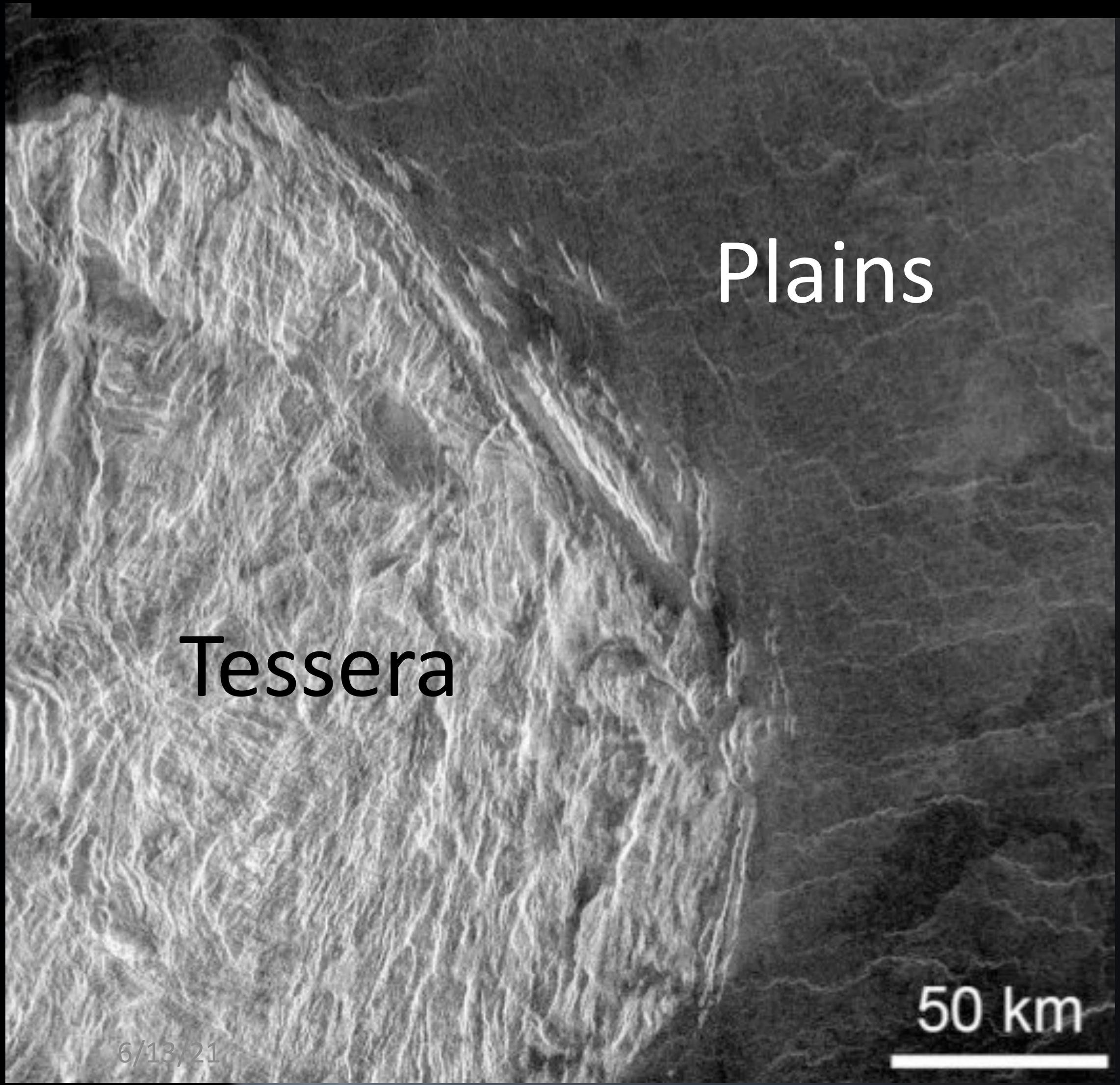
550 km across
225 m/pixel

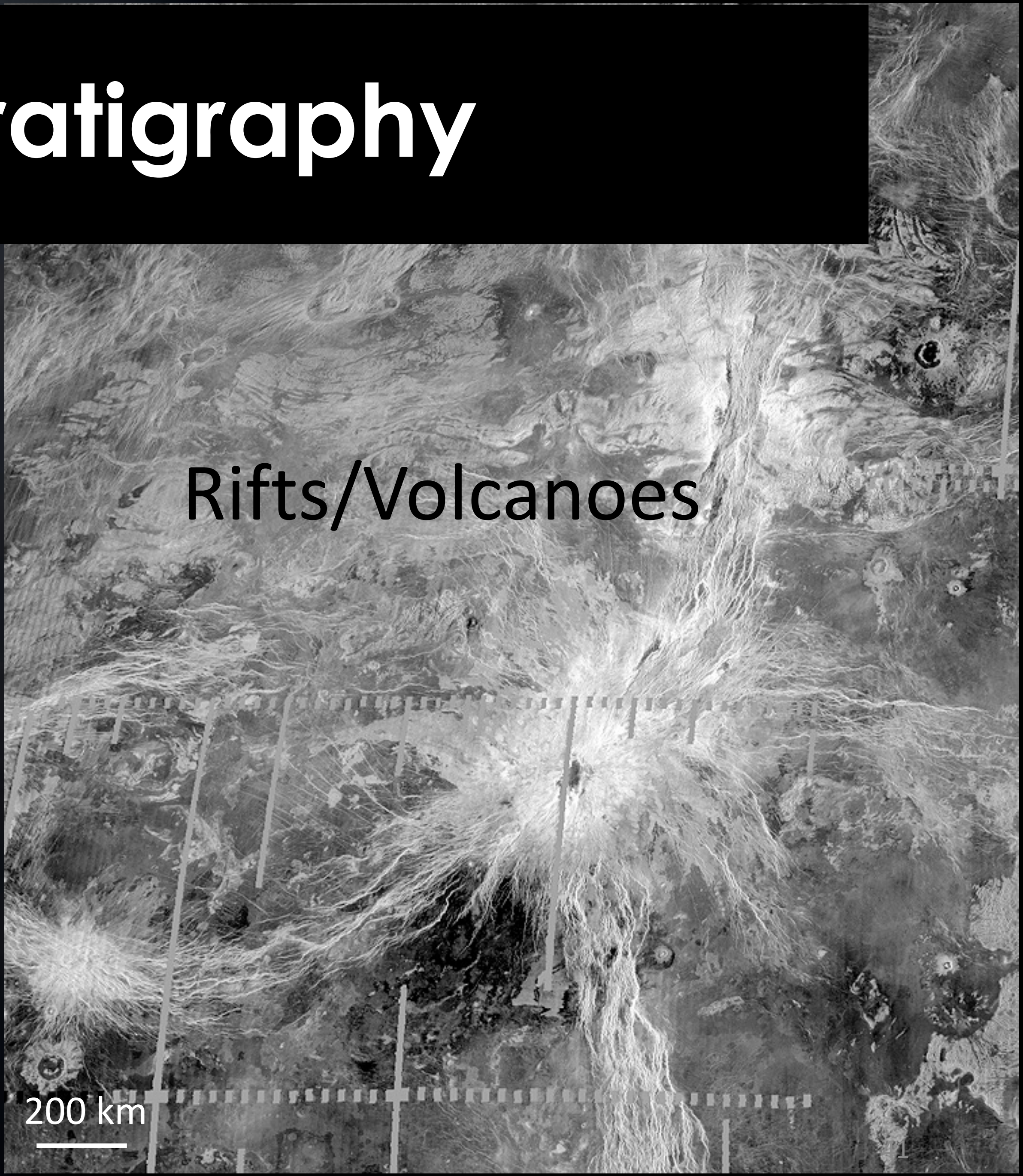


Topographic map of Venus, Daniel Machacek

-3 km to 11 km elevation

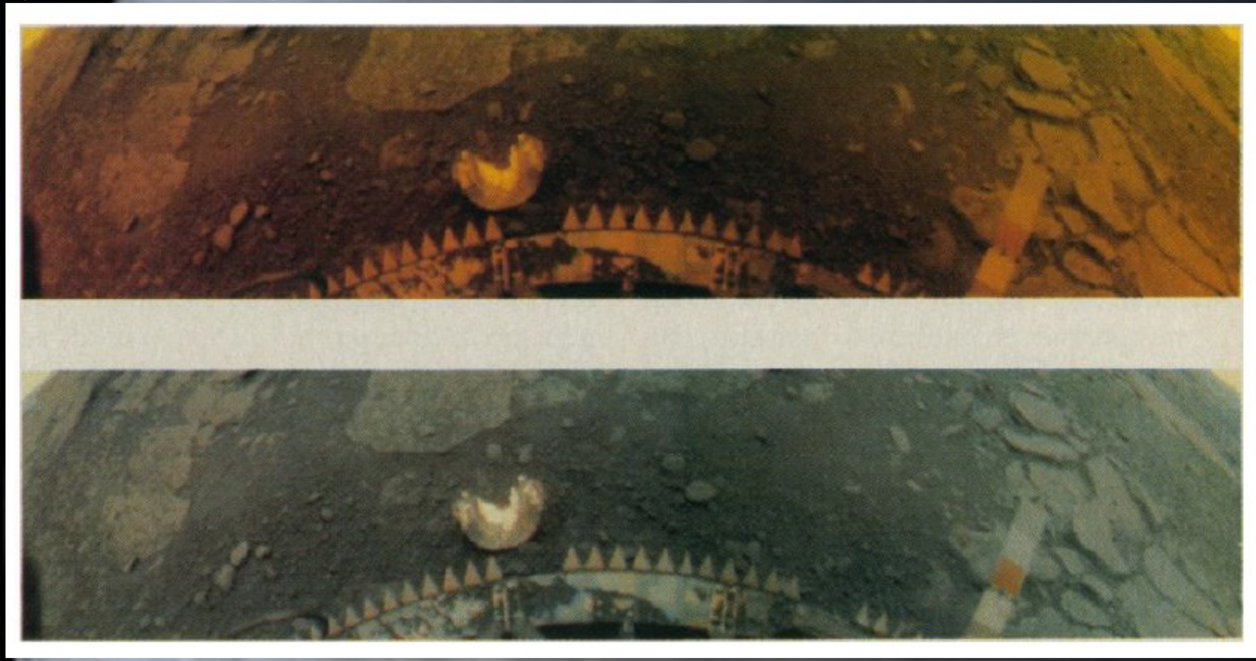
A General Stratigraphy





Venus Surface Chemistry

(Pieters et al., 1986)



(Fegley et al., 1997)

TABLE IV

Gamma Ray Analyses of the Surface of Venus[a]

Lander	K (wt%)	U (ppm)	Th (ppm)
Venera 8	4.0±1.2	2.2±0.7	6.5±2.2
Venera 9	0.47±0.08	0.60±0.16	3.65±0.42
Venera 10	0.30±0.16	0.46±0.26	0.70±0.34
Vega 1	0.45±0.22	0.64±0.47	1.5±1.2
Vega 2	0.40±0.20[b]	0.68±0.38	2.0±1.0

[a] Table from Surkov et al. (1987*a*,*b*).
[b] Compare to 0.1±0.08 wt% from XRF analysis on Vega 2.

TABLE V

Major Element Composition of the Surface of Venus and of Some Terrestrial Rocks

	Mass Percent ($\pm 1\sigma$)					
Oxide	Venera 13[a]	Venera 14[a]	Vega 2[b,e]	N-MORB[f]	Leucitite[g]	Lamprophyre[h]
SiO_2	45.1±3.0	48.7±3.6	45.6±3.2	48.77	46.2	46.3
TiO_2	1.59±0.45	1.25±0.41	0.2±0.1	1.15	1.2	2.6
Al_2O_3	15.8±3.0	17.9±2.6	16±1.8	15.90	14.4	13.5
FeO[c]	9.3±2.2	8.8±1.8	7.7±1.1	9.82	8.09	11.0
MnO	0.2±0.1	0.16±0.08	0.14±0.12	0.17	0.0	0.21
MgO	11.4±6.2	8.1±3.3	11.5±3.7	9.67	7.0	9.1
CaO	7.1±0.96	10.3±1.2	7.5±0.7	11.16	13.2	10.7
Na_2O[d]	2±0.5	2.4±0.4	2	2.43	1.6	3.1
K_2O	4.0±0.63	0.2±0.07	0.1±0.08	0.08	6.4	2.9
SO_3	1.62±1.0	0.88±0.77	4.7±1.5			
Cl	<0.3	<0.4	<0.3			
Total	98.1	98.7	95.4	99.15[f]	98.09	99.41

[a] Surkov et al. (1984).
[b] Surkov et al. (1986).
[c] All Fe reported as FeO for all analyses.
[d] Calculated by Surkov et al. (1984,1986).
[e] In addition to Cl, Surkov et al. (1986) also report the following upper limits (in mass %): Cu, Pb<0.3; Zn<0.2; Sr, Y, Zr, Nb, Mo<0.1; As, Se, Br<0.08.
[f] N-type, or normal MORB (Wilson 1989). Also contains 0.09% P_2O_5 and 0.30% H_2O.
[g] Leucitite, an alkaline basalt (Philpotts 1990). Also contains 0.4% P_2O_5.
[h] Lamprophyre, which is an ultrapotassic rock (Wilson 1989). Also contains 0.9% P_2O_5, 2.6% H_2O, and 2.5% CO_2.

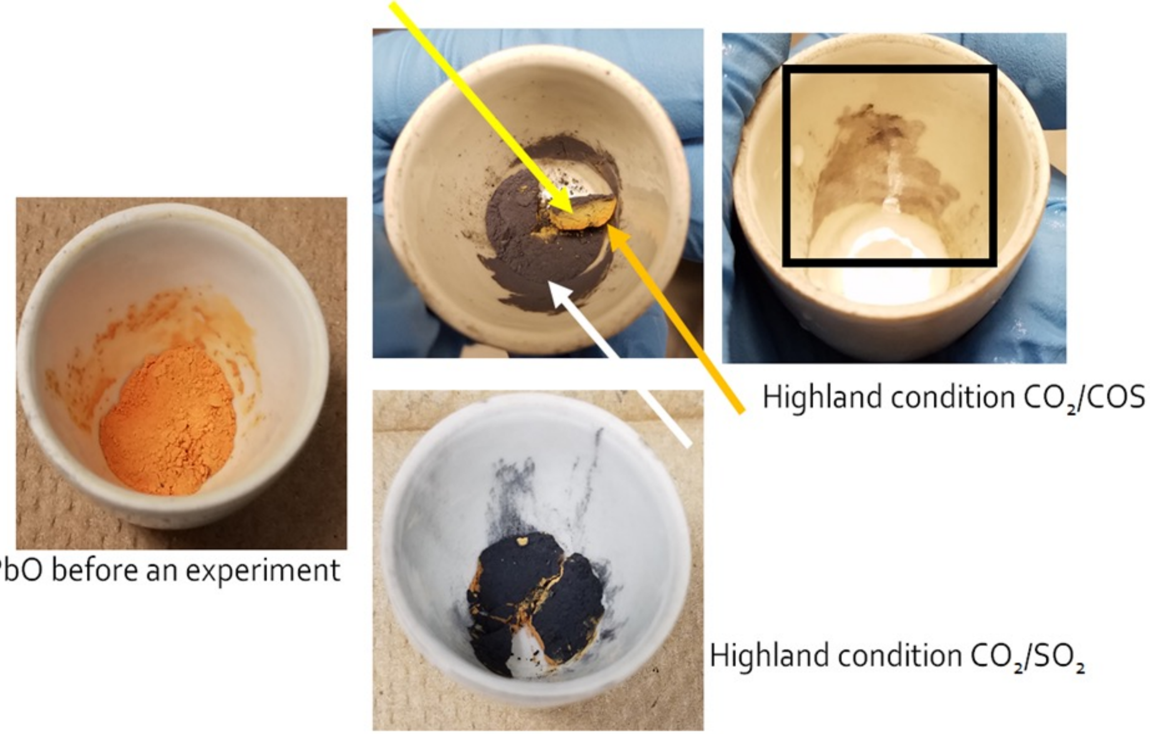
Venus Petrology

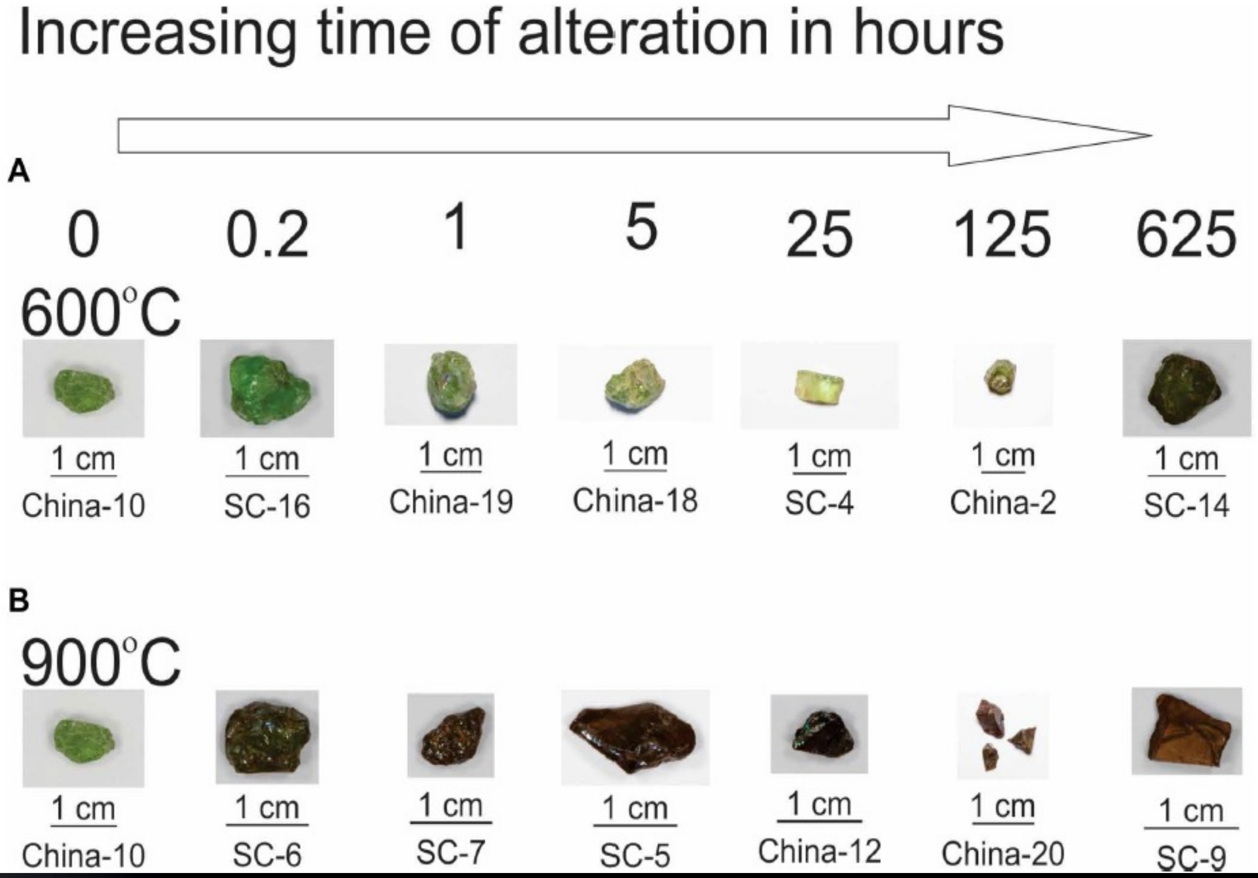
TABLE VI
Normative Mineralogy of the Venera and Vega Landing Sites[a]

		CIPW Norm (Mass %)		
Mineral		Vega 2	Venera 13	Venera 14
Orthopyroxene	En	20.8	0.0	14.2
	Fs	9.2	0.0	10.1
Clinopyroxene	Wo	0.8	9.4	5
	En	0.5	5.8	2.8
	Fs	0.2	3.0	2.0
Olivine	Fo	7.4	16.2	2.6
	Fa	3.6	9.3	2.1
Plagioclase	Ab	17	0.0	17.0
	An	39.3	13.1	40.6
K-feldspar	Or	0.7	10.2	1.2
Feldspathoids	Lc	0.0	11.2	0.0
	Ne	0.0	18.8	0.0
Oxides	Il	0.4	3.0	2.4
Total		99.9	100.0	100.0

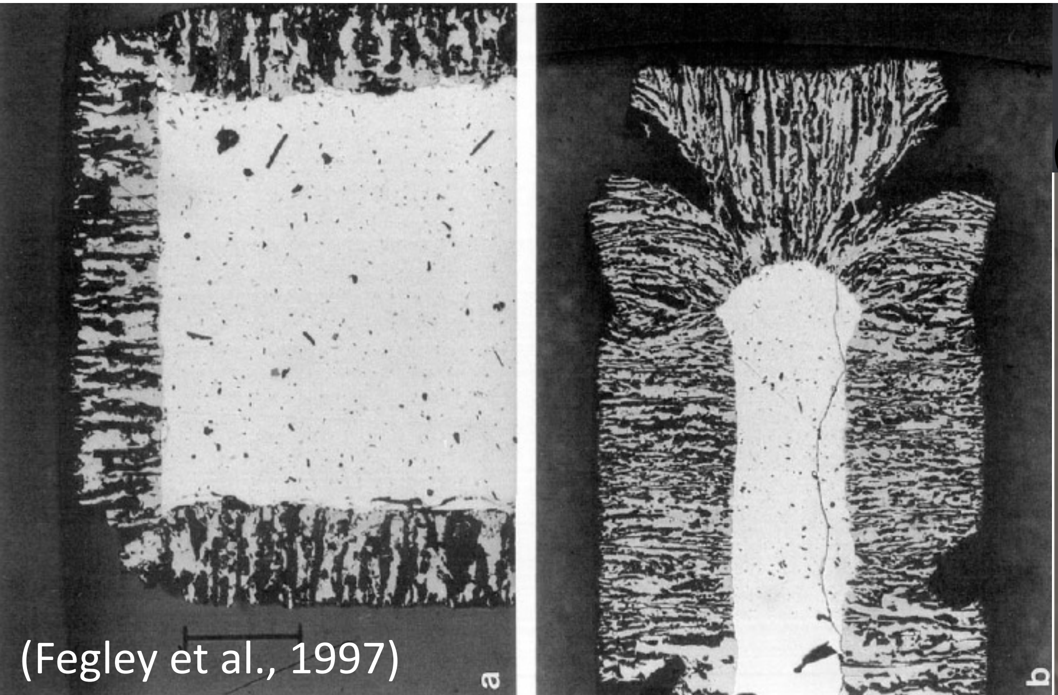
[a] Calculated by Kargel et al. (1993) on a volatile-free basis. En: enstatite; Fs: ferrosilite; Wo: wollastonite; Fo: forsterite; Fa: fayalite; Ab: albite; An: anorthite; Lc: leucite; Ne: nepheline; Il: ilmenite.

(Fegley et al., 1997)

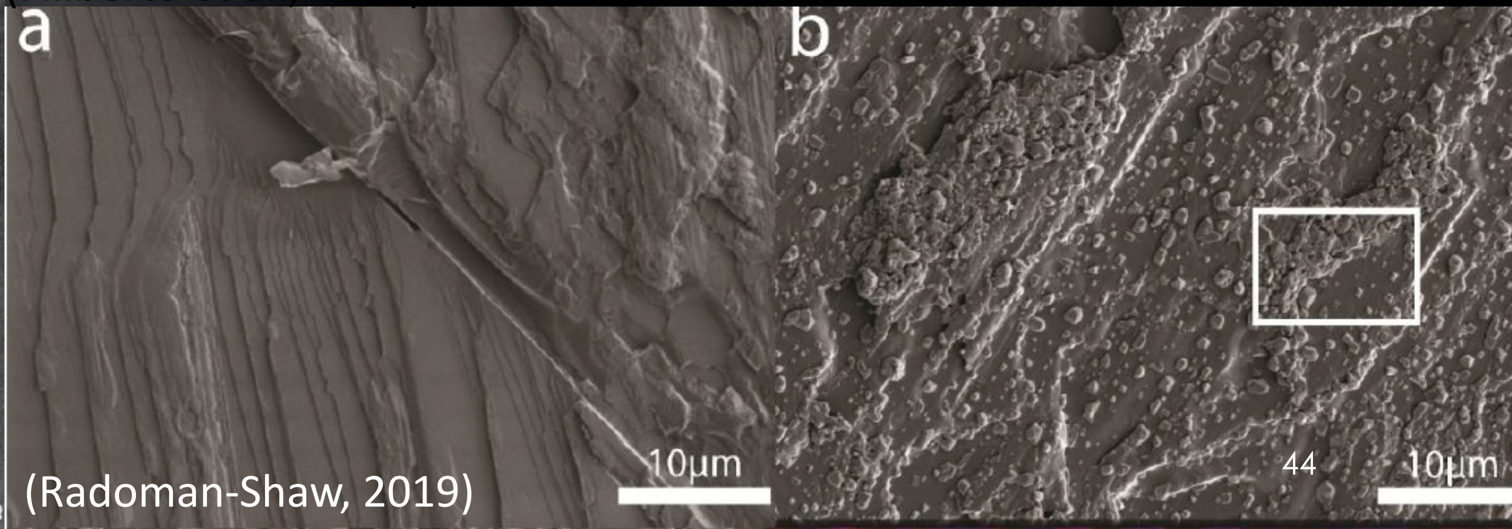




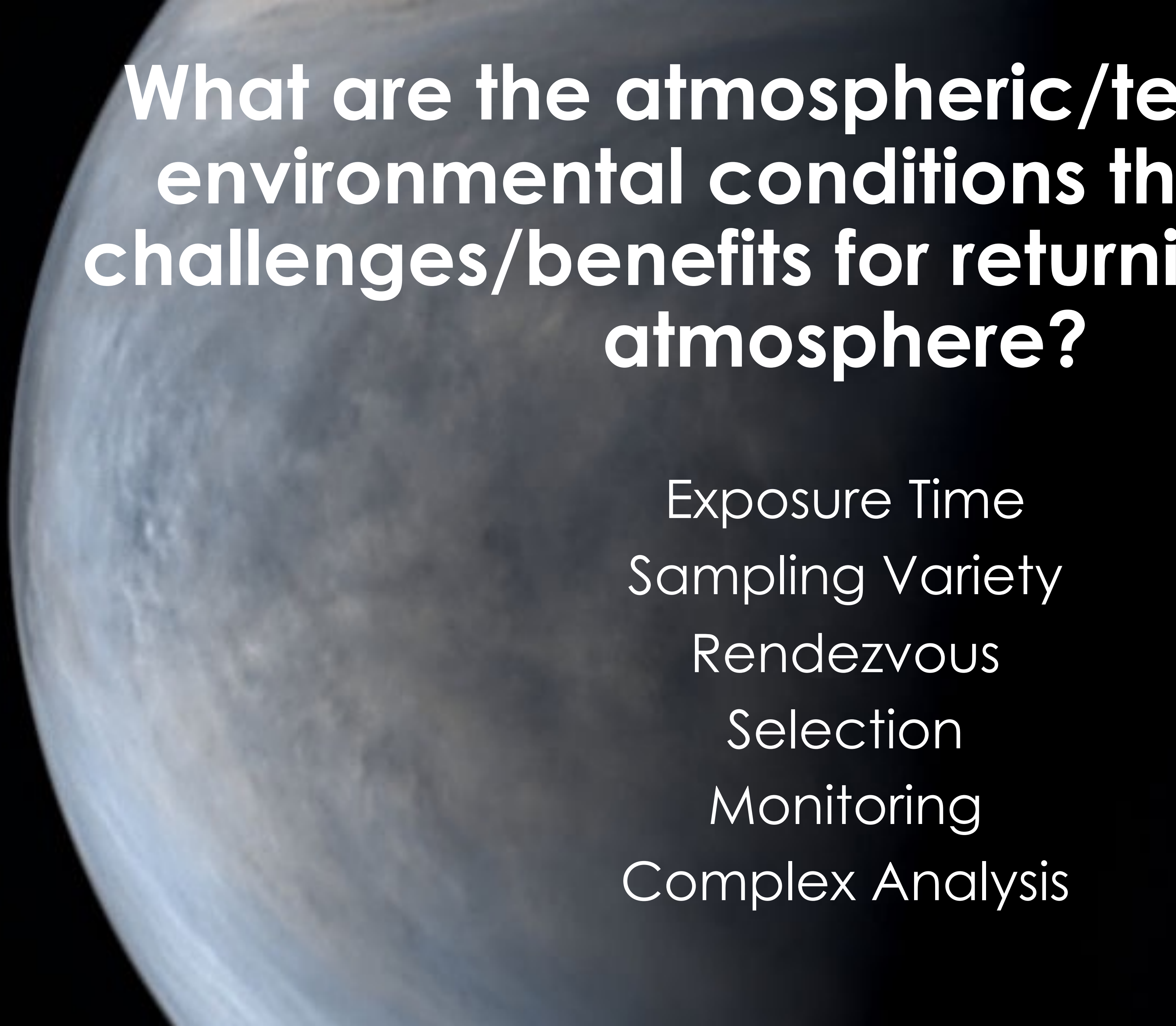
(Filiberto et al., 20



(Fegley et al., 1997)



(Radoman-Shaw, 2019)



What are the atmospheric/temperature environmental conditions that can be challenges/benefits for returning to upper atmosphere?

Exposure Time

Sampling Variety

Rendezvous

Selection

Monitoring

Complex Analysis

Next

Dr. Jim Cutts (JPL) - Venus Aerial Platforms

The foundations of an aerial laboratory

Dr. Gary Hunter (NASA Glenn) - High-Temperature Technologies

Withstanding the heat

Dr. Kathryn Bywaters (Honeybee Robotics) - Sample Capture

Hitting (and grabbing) paydirt