ANCIENT VENUS

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Monday, July 25, 2022

8:45 a.m.	Accretion History Early Atmosphere (+ Noble Gas)
10:45 a.m.	Atmosphere Formation and Evolution
1:20 p.m.	Habitability and Oceans

Tuesday, July 26, 2022

9:00 a.m.	Socializing Venus
9:25 a.m.	Tesserae
11:00 a.m.	Tectonics/Dynamics
1:45 p.m.	Venus Samples!!!
6:00 p.m.	Venus Social Hour

Monday, July 25, 2022
ACCRETION HISTORY EARLY ATMOSPHERE (+ NOBLE GAS)
8:45 a.m.

Times	Authors (*Presenter)	Abstract Title and Summary
8:45 a.m.	Treiman A. *	*Introduction to Ancient Venus Conference*
9:00 a.m.	Lambrecht M. *	*Early Solar System Planetary Accretion, Differentiation*
9:20 a.m.	Jacobson S. A. * Dobson C.	*What Does It Mean to Have No Moon? Evidence for an Early or No Giant Impact on Venus* **[#2030]** The lack of venusian moon is unexpected given the likelihood of moon formation after a giant impact, however if the last giant impact on Venus is early unlike Earth's Moon-forming event, then planetary flybys could remove a Venusian moon.
9:35 a.m.	Bijkerk A. K. *	*Venus, the Hot Brake Hypothesis* **[#2024]** Venus's primordial spinning energy was converted to heat due to a mixture of two earlier hypotheses, the chaotic mantle-core boundary resonance and the passing of the chaotic zone of resonance between obliquity and precession cycles.
9:50 a.m.	Kane S. R. * Vervoort P. Horner J. Pozuelos F. J.	*Could the Migration of Jupiter have Accelerated the Atmospheric Evolution of Venus?* **[#2005]** We present the results of a dynamical study that explores the effect of Jupiter's location on the orbital eccentricity of Venus and subsequent potential water-loss scenarios.
10:05 a.m.	Panel Discussion *	*In What Ways Did Venus Form Like Earth and In What Ways Differently*
10:35 a.m.		Break

Monday, July 25, 2022
ATMOSPHERE FORMATION AND EVOLUTION
10:45 a.m.

Times	Authors (*Presenter)	Abstract Title and Summary
10:45 a.m.	Thompson M. *	*Outgassing Experiments*
11:05 a.m.	Avice G. * Parai R. Jacobson S. Labidi J. Trainer M. G. Petkov M. P.	*Noble Gases and Stable Isotopes Track the Origin and Early Evolution of the Venus Atmosphere* **[#2018]** Noble gases and stable isotopes teach us a lot about the origin and early evolution of the Venus atmosphere. The existing dataset already provides important information but needs to be completed by future space missions.
11:20 a.m.	Zahnle K. J. *	*Ancient Gases of Ancient Venus* **[#2013]** The noble gases preserve a sparse but relatively accessible record of Venus's history. Given the difficulty in obtaining access to other records, they are likely to play an outsized role in the retelling of Venus's story for the foreseeable future.
11:35 a.m.	Head J. W. * Wilson L. Ivanov M. A. Wordsworth R. D.	*The Origin of Venus' Atmosphere: Geologically Recent or Ancient (Fossil)?* **[#2011]** Using global geologic map data for an inverse model, we test the hypothesis that an earlier Earth-like Venus atmosphere persisted into the last 20% of Venus' history; we find that the current atmosphere must be 'fossil', dating from the first 80%.
11:50 a.m.	Garvin J. B. Getty S. A. Arney G. N. Johnson N. M. * Kohler E.	*DAVINCI Mission Contributions to Ancient Venus Science* **[#2015]** The DAVINCI mission will address an ensemble of Ancient Venus questions via is 7 flight instruments, with emphasis on the chemistry of the atmosphere and surface-atmosphere interactions in a local region of Alpha Regio.
12:05 p.m.	Weller M. B. * Kiefer W. S.	*Becoming Venus: How the Mantle, Volcanism, and Physics-Backed Models of Global Tectonic Evolution Can Self-Consistently Explain Observations for Venus* **[#2002]** Venus of Today / Created, changed, inside out. / The surface tells all.
12:20 p.m.	Runyon K. D. * Barnouin O. S. Izenberg N. Ernst C. M. Stickle A. M.	*Atmospheric Effects on Crater Size: Preliminary Results from a Pilot Study* **[#2016]** Experimental craters formed in atmosphere are smaller but steeper than craters formed in vacuum. Crater depth:diameter on Venus may be a proxy paleo-atmosphere indicator.
12:35 p.m.	Panel Discussion *	*Atmospheric Effects on Crater Size*
1:05 p.m.		Break

Monday, July 25, 2022
HABITABILITY AND OCEANS
1:20 p.m.

Times	Authors (*Presenter)	Abstract Title and Summary
1:20 p.m.	TBD *	*Modeling and Oceans*
1:40 p.m.	Turbet M. * Leconte J. Fauchez T. Selsis F. Bolmont E. Charnay B. Chaverot G. Ehrenreich D. Forget F. Lovis C. Marcq E. Millour E.	*Day-Night Cloud Asymmetry Inhibits Early Ocean Formation on Venus and Telluric Planets* **[#2009]** We will present the results of new 3-D Global Climate Model (GCM) simulations aimed at reproducing the conditions of primordial surface water condensation and thus of the formation of ancient oceans on Venus.
1:55 p.m.	Bullock M. A. * Grinspoon D. H.	*The Transformation of Venus' Clouds Before and After Water Loss* **[#2029]** If Venus once had an ocean with water/ice clouds, they must have transitioned to sulfuric acid clouds sometime after Venus' water was lost. We discuss how understanding this transition places constraints on the formation of its current atmosphere.
2:10 p.m.	Gillmann C. *	*Getting Rid of Venus' Oceans: Volatile Exchanges on Ancient Venus* **[#2008]** Venus' past surface conditions are still largely unknown. Both dry hot, and wet mild scenarios have been suggested. We consider the problems each scenario can generate and define under what conditions Venus could have harbored temperate conditions.
2:25 p.m.	Way M. J. *	*Early Venus Habitability*
2:40 p.m.	Panel Discussion *	*Early Oceans or Not?*

Tuesday, July 26, 2022
SOCIALIZING VENUS
9:00 a.m.

Times	Authors (*Presenter)	Abstract Title and Summary
9:00 a.m.	Shaner A. J. * Buxner S. R. Balcerski J. Izenberg N. R. Kiefer W. S. Treiman A. H.	*Venus Science and Exploration and Public Engagement: A Proposal* **[#2014]** The LPI proposes to create and coordinate an initiative to provide public engagement guidance for the Venus science community and act as a hub for collecting and sharing information about the Venus community's public engagement efforts.
9:15 a.m.	Panel Discussion *	*Building the Community*

Tuesday, July 26, 2022
TESSERAE
9:25 a.m.

Times	Authors (*Presenter)	Abstract Title and Summary
9:25 a.m.	Ernst R. E. * Dean R. El Bilali H. Buchan K. L.	*Deciphering 4 Billion Years of Geological History Potentially Recorded in Venusian Tesserae* **[#2023]** Tesserae are the key to recognizing a potential 4 billion years of geological history on Venus.
9:40 a.m.	Whitten J. L. * Campbell B. A.	*Tesserae: Identifying Distinct Deposits Using Surface Roughness Characteristics Derived from Magellan Data* **[#2028]** Venus tesserae can be divided into two classes based on cm-scale surface roughness.
9:55 a.m.	Roberts E. K. * Treiman A. H. Eggers G. L.	*Multiple Tectonic and Volcanic Events: Gina Crater Area, Venus* **[#2006]** The Gina Crater area shows multiple episodes of tectonism and volcanism. The crater lies on the boundary of regional plains and tessera/lineae material. Tectonic and volcanic activity overlapped in time; deformation of Gina implies recent events.
10:10 a.m.	Gilmore M. S. * Santos A. R.	*The Mineralogical Record of Ancient Venus Climates Preserved in the Tesserae* **[#2021]** We propose several possible mineralogic assemblages formed during the formation and weathering of tessera terrain. These histories are testable using NIR spectroscopy if the emissivity signatures of minerals subject to Venus conditions are known.
10:25 a.m.		DISCUSSION
10:40 a.m.		Break

Tuesday, July 26, 2022
TECTONICS/DYNAMICS
11:00 a.m.

Times	Authors (*Presenter)	Abstract Title and Summary
11:00 a.m.	Davaille A. *	*Global Mapping and Major Questions*
11:15 a.m.	Ivanov M. A. * Head J. W.	*Fundamental Questions About 'Ancient Venus' Revealed by Global Geologic Mapping: Identification of Future Challenges and Opportunities* **[#2003]** A global geological map of Venus compiled at a scale of 1:10M permits the identification of major unknowns and outstanding questions. We outline and discuss twelve of these compelling questions and challenges for future Venus research.

11:30 a.m.	James P. B. * King S. D.	*Venus's Mantle: Key for Characterizing Ancient Surface Mobility* **[#2027]** We argue here that extensive records of ancient Venus are preserved beneath the surface. Depleted mantle lithosphere is identifiable in the gravity field, and the observed COM-COF offset is an important constraint on convection models.
11:45 a.m.	Kiefer W. S. * Weller M. B.	*Venus, Earth's Divergent Twin: Observations Constraining the Transition from a Mobile Lid Convection Planet to a Stagnant Lid Convection Planet* **[#2007]** Venus in the past had a mobile surface, producing Ishtar Terra by large-scale lateral convergence. Venus today has an immobile surface, with limited rifting and no hotspot tracks. This transition in tectonic style is likely linked to climate change.
12:00 p.m.	King S. D. * Euen G. T.	*When and How Did Venus Resurfacing Begin?* **[#2012]** So few craters here, / And a balanced figure. / The secret lies within.
12:15 p.m.	Buck W. R. *	*Application of a Thin-Sheet, Lower Crustal Flow Model to Relate Crustal Rheology and Past Thermal Conditions to Surface Topography and Deformational Features on Venus* **[#2017]** The high surface temperatures on Venus are likely to result in a weak lower crust there. Because this layer should be thin compared to its lateral extent a fairly simple model can be used to relate mantle flow to surface features and topography.
12:30 p.m.	Weller M. B. * Kiefer W. S.	*Creating the Bridge: Melting and Volcanism In, and On, Active and Stagnant Lid Planets* **[#2026]** Active lid Planet / What if instead stagnant? / How does it differ?
12:45 p.m.	Treiman A. H. * Filiberto J.	*Chemistry of Venus' Recent Basalts as Clues to its Ancient Past* **[#2001]** New chemical analyses of Venus' surface will likely be first of 'recent' basalts. These analyses could contain evidence of ancient aqueous processes, as depletions/excesses of fluid mobile (e.g. K, Ba) or some HFS (e.g. Ti, Nb) elements.
1:00 p.m.		DISCUSSION
1:30 p.m.		Break

Tuesday, July 26, 2022
VENUS SAMPLES!!!
1:45 p.m.

Times	Authors (*Presenter)	Abstract Title and Summary
1:45 p.m.	Santos A. *	*How Would We Recognize a Meteorite from Venus?*
2:00 p.m.	Cabot S. H. C. * Laughlin G.	*Lunar Exploration as a Probe of Ancient Venus* **[#2020]** Asteroid impacts at Venus would have ejected considerable quantities of surface material during the planet's posited Earth-like era. We investigate the prospects of recovering lightly-shocked, ancient venusian meteorites in the lunar regolith.
2:15 p.m.	Kroupa M. K. * Coleman N. C.	*Adv, Maximal Endurance, VTOL and Sample Return Capable, Mission Agnostic Planetary 4D Explorer[4DPE]* **[#2010]** A highly efficient, maximally versatile, large payload capable, optimally powered ultra-light glider-rover and bot networks to explore the entire surface and atmosphere of Venus or other bodies in 4D for decades with possible sample return.
2:30 p.m.	Treiman A. *	*Closing Remarks*

Tuesday, July 26, 2022
VENUS SOCIAL HOUR
6:00 p.m.
Details and connection information will be provided during the conference.

Ancient Venus

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Ancient Venus

Abstracts

NOBLE GASES AND STABLE ISOTOPES TRACK THE ORIGIN AND EARLY EVOLUTION OF THE VENUS ATMOSPHERE. G. Avice[1], R. Parai[2], S. Jacobson[3], J. Labidi[1], M. G. Trainer[4], M. P. Petkov[5] [1]Institut de physique du globe de Paris, Université Paris Cité, CNRS, France, avice@ipgp.fr, [2]Washington University in St. Louis, USA, [3]Michigan State University, USA, [4]NASA Goddard Space Flight Center, USA, [5]NASA Jet Propulsion Laboratory, California Institute of Technology, USA.

Introduction: The composition of the Venus atmosphere informs us about the entire geological history of Earth's sister planet. Knowing the elemental abundances and isotopic ratios of noble gases and other volatile elements in the Venus atmosphere has always been a high priority scientific target since it could open a window on the origin and early evolution of the entire planet [1]. In this contribution see also ref. [2], the present state of knowledge on the origin and early evolution of the Venus atmosphere and the missing information will be presented. Recent discoveries about the origins and evolution of volatile inventories on Earth, Mars and in other solar system reservoirs have raised new questions, which motivate new investigations. Planned and potential space mission investigations dedicated to noble gases and stable isotopes will be presented.

Origin of the Venus atmosphere: Only little is known about the origin of volatile elements in the Venus atmosphere and by extension the entire planet. Venus is enriched in light noble gases compared to and Mars [3]. The elemental Ar/Ne ratio is close to chondritic values, whereas the isotopic composition of neon is solar-like. This discrepancy could be explained by the delivery of neon-poor cometary material to the Venus atmosphere. Russian missions operating during the 70's revealed that the Venus atmosphere does contain Kr and Xe but the abundance of xenon is largely unconstrained. Unfortunately, the isotopic compositions of krypton and xenon are also unknown, thereby preventing clear conclusions regarding the exact mixture of chondritic, solar and cometary volatile elements brought to the Venus atmosphere.

Early evolution: *Atmospheric escape.* Atmospheric escape processes are key processes controlling the composition of a planetary atmosphere and have thus a strong impact on a planet's habitability. The very high D/H ratio measured in the Venus atmosphere [4] is a strong indication that Venus suffered from hydrogen escape although knowing the starting abundance and isotopic composition of hydrogen (and thus water) is extremely challenging. Precise determinations of the isotopic compositions of nitrogen and xenon in the atmosphere of Venus could help to estimate the extent of atmospheric loss and determine what ancient Venus looked like.

Outgassing. Some isotopes of noble gases (^{40}Ar, ^{129}Xe, ^{4}He) have been produced by decay of extinct (*e.g.,* ^{129}I) or extant (*e.g.,* ^{40}K, ^{238}U) radioactive nuclides in silicate portions of Venus. With time, they have been progressively degassed into the atmosphere. Measuring the relative excesses of these isotopes allows to shed light on the outgassing history of a planet. There is little radiogenic ^{40}Ar in the Venus atmosphere compared to Earth, suggesting that Venus is less degassed compared to Earth [5]. However, this comparison relies on a very uncertain elemental K/U ratio for bulk Venus. Knowing the isotopic composition of xenon the Venus atmosphere is essential to refine our understanding of Venus' geodynamical history.

Future directions: Space missions planned for the early 2030's will undoubtedly unveil many details about Venus' origin and early history. For volatile elements, the DAVINCI mission will be revolutionizing our views regarding the origin and evolution of the Venus atmosphere. The DAVINCI probe will conduct in situ sampling and measurement of noble gases and noble gases during its hour-long descent to the surface. Importantly, DAVINCI will also be able to construct atmospheric profiles of the D/H ratio to better understand the variations of this ratio with altitude [6].

Returning to Earth a sample from the Venus atmosphere could represent one of the next steps of Venus exploration. This type of investigation is certainly challenging, especially to ensure that the atmospheric sample stays pristine and is not modified by the sampling or return protocols. However, having a well-curated atmospheric sample from Venus in Earth laboratories would allow a thorough characterization of the elemental and isotopic composition of volatile elements present in the Venus atmosphere with extremely high precision, allowing to run an exhaustive exercise of comparative planetology between Earth, Mars and Venus.

Acknowledgments: The International Space Science Institute is acknowledged its organization of the "Venus: Evolution through time" workshop. G. A. acknowledges financial support from the Centre National d'Etudes Spatiales (CNES). **References:** [1] Glaze et al. 2018. *Space Sci. Rev.* **214**:89. [2] Avice et al. 2022. *Space Sci. Rev.* ***submitted****. [3] Chassefière et al. 2012. Planet. & Space Sci.* **63-64**:15-23. [4] Donahue et al. 1982. *Science* **216**:630-633. [5] Kaula 199. *Icarus* **139**:32-39. [6] Glaze et al. 2017. **2017 IEEE Aerosp. conf**.

VENUS, THE HOT BRAKE HYPOTHESIS. A. K. Bijkerk[1]

Introduction: It is assumed that the accretion process of protoplanet Venus originally emerged much similar to Earth. Then it appears that the current enigmatic condition of Venus could be consistent with the planet having exchanged its rotational kinetic energy for heat energy at some moment in time. For instance, the rotational energy of Earth is ~2E32 Joule. Heating up from freezing and subsequently boiling away all earth oceans would require ~1E30 Joule[2], only a half percent of Earth's rotational energy. Hence, if Earth stopped spinning, perhaps due to internal friction forces, the resulting heat breaking to the surface, would be ample to evaporate the oceans and heat up the surface substantially, creating an event that could be similar to the 'resurfacing' of Venus. Moreover several chemical reactions would occur; most notably: virtually all carbon in Earth's mantle and lithosphere would either burn or have a reduction reaction with water vapor resulting in $C+2H_2O \rightarrow CO_2 + 4H_2$. The Hydrogen gas would be outgassed into space eventually, whilst the CO_2 would form a dense atmosphere, as is seen on Venus.

Hence, if Earth would seize rotating, the resulting internal heat would break to the surface eventually, and this would turn the planet into a condition much similar to Venus. Therefore we have to consider hypotheses for possible mechanisms that could have caused Venus to stop spinning and consequently, why it did not happen to Earth.

Rotation history of Venus: Van Hoolst 2015[[1]] an references herein compile the notion that Venus's current slow retrograde spin cannot be taken as an indication for a primordial slow rotation. '*Instead of being locked in a spin– orbit or spin–synodic resonance, the rotation of Venus is thought to be the result of a balance between solid-body tidal torques, which drive Venus to synchronous rotation, and atmospheric torques, which drive it away'* Assuming that proto-planet Venus rotated in a similar manner as other terrestrial planets did, the gravitational tides and friction torques at the core mantle boundary may have been more pronounced than other planets and did decelerate the rotation of Venus, also the dense atmosphere is thought to have contributed.

Correia et al (2003)[[2]] propose that the process may have been enhanced by Venus passing the chaotic zone, when resonance between both precession and obliquity cycles are approximately equal, leading to extreme perturbations of the direction of the spin axis, the chaotic zone[3]. However numerical simulations[4] suggest that the primordial rotation should have been much less than Earth's rotation, while the process was continuous, which limits the rate of rotational energy depletion.

Touma and Wisdom (2001)[[5]] have a different approach, resonance in the core mantle boundary of terrestrial planets as a result of orbital forcings (Milankovitch cycles). They have identified and derived the main resonance contributions near the principal core-mantle precession resonances. This would cause the core rotation axis to lose alignment with the mantle, which would lead to considerable dissipation of rotational energy into heat. For Earth the different geographic polarity of the 'inner inner' core[[6]] could be evidence of such an event as well as extensive volcanic activity in the geologic past (Siberian traps). For Venus, if the planet had been born spinning retrograde, the resonance process would be much more intense and they propose that this could have led to the resurfacing event of Venus[[7]]. There is some speculation of some primordial massive impacts in the earliest moments of the solar system, that could have caused retrograde spin, however nowadays there is little support of such a notion.

Discussion: We evaluated both hypotheses and we must conclude that neither could explain the current condition of Venus in full. However elements of both combined may do so.

The hypothesis of Correia et al (2003) is based upon the planet passing a chaotic zone in which resonance between precession- and obliquity cycles, are causing extreme oscillations of the spin axis of the mantle of the planet. However, it does not consider internal core-mantle resonance and it seems not sufficient to explain the extreme heat generation as seen on Venus.

The hypothesis of Touma and Wisdom (2001) is based on resonance in the core-mantle boundary and it could explain Venus's current hot condition if its primordial rotation was retrograde. However there appears to be little support of the latter. They do not

[1] Independent researcher, Marsmanhove 54, 2726 CP Zoetermeer The Netherlands

[2] Volume oceans 1.33E+09km3; specific heat water times 100(k) times 4.18 J/g times evaporating 2257 J/g = 1.26E30J

consider extreme mantle spin axis oscillations due to passing the ‘chaotic zone’.

It appears that merging both hypotheses into the “hot brake hypothesis” may result in a workable idea that answers to all enigmatic features of Venus, if both resonance of core-mantle boundary would have happened during passage of the chaotic zone of the resonance of the precession- and obliquity cycle, the resulting chaotic spinning could have resulted in the planet ‘toppling over’ from prograde- to retrograde spinning while dissipating most of its spinning energy into heat.

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[1] Van Hoolst, T. (2015). Treatise on Geophysics, 121–151. doi:10.1016/b978-0-444-53802-4.00168-8
[2] Correia, A. C. M. Et al (2003) Icarus, 163(1), 1–23. doi:10.1016/s0019-1035(03)00042-3
[3] J. Laskar & P. Robutel Nature volume 361, pages 608–612 (1993)
[4] Correia, A. C. M., & Laskar, J. (2003). Icarus, 163(1), 24–45. doi:10.1016/s0019-1035(03)00043-5
[5] J. Touma and J. Wisdom (2001), The Astronomical Journal, 122 : 1030È1050, August
[6] Wang, T., et al (2015). Nature Geoscience, 8(3), 224–227. doi:10.1038/ngeo2354 https://www.nature.com/articles/ngeo2354
[7] Schaber, G. G., et al. 1992, International Colloquium on Venus (LPI Contrib. 789) (Houston : Lunar Planet. Inst.), 100

Application of a thin-sheet, lower crustal flow model to relate crustal rheology and past thermal conditions to surface topography and deformational features on Venus. W. R. Buck, Lamont-Doherty Earth Observatory of Columbia University, 61 Route 9W, Palisades, NY 10964, email: buck@ldeo.columbia.edu.

Introduction: Recent analysis of structurally delimited crustal blocks in the Venus lowlands led Byrne et al. [1] to suggest that they are deformed due to flow stresses generated by mantle convection. Those authors note that the blocks "show evidence for having been rotated and/or moved laterally relative to one another, akin to jostling pack ice." This leads Byrne etal [1] to argue for a "mobile lid" tectonics on Venus that involves partial decoupling from the underlying mantle flow by a weak lower crust. Such a weak lower crust is likely due to the high surface temperatures in Venus [2-4]. A simple 1.5 dimensional numerical treatment (i.e. a cross-sectional, thin channel model) was used in [2] to treat such partial decoupling and show that the observed range of Venus topography could be produced for a reasonable crustal rheology given a large scale pattern of mantle flow on Venus. More particularly, those models and later physical models [5] showed that crustal extension could result in areas of active mantle convergence.

A 2.5 dimensional model of channel flow was developed to consider the effect of terrestrial plate tectonic motions on variations in mantle asthenospheric thickness [6]. Since the asthenosphere was assumed to be less dense than underlying mantle, variations in the asthenospheric layer thickness could be related to ocean bathymetry. That effort successfully related the history of oceanic plate motions to the distribution of bathymetry at plate spreading centers.

Application of the 2.5 dimensional approach to the problem of crustal channel flow on Venus is straightforward, though it requires several major assumptions. The effort would be to relate topographic and surface deformational features to assumed distributions of mantle flow, mantle heat flow and surface temperature. A temperature dependent crustal rheology would also be a key component of these models. The effect of possible past surface temperature and mantle thermal and flow conditions would be considered in these models.

References: [1] Byrne P.K. et al. (2021) A globally fragmented and mobile lithosphere on Venus, PNAS, 118, 26, 1-8. [2] Buck W. R. (1992) Global decoupling of crust and mantle: Implications for topography, geoid, and mantle viscosity on Venus. *GRL, 19*, 2111–2114. [3] Arkani-Hamed, J. (1993) On the tectonics of Venus. *PEPI, 76*, 75–96. [4] Ghail, R.C. (2015) Rheological and petrological implications for a stagnant lid regime on Venus. *Planet. Space Sci. 113–114*, 2–9 (2015). [5] Buck, W. R. and Sokoutis D. (1994) Analogue model of gravitational collapse and surface extension during continental convergence, Nature, 369,737-740. [6] Buck W.R. et al. (2009), Constraints on asthenospheric flow from the depths of oceanic spreading centers: The East Pacific Rise and the Australian-Antarctic Discordance, *G-cubed, 10*, Q09007.

The Transformation of Venus' Clouds Before and After Water Loss. M. A. Bullock[1] and D. H. Grinspoon[2], [1]Science and Technology Corp. bullock@stcnet.com [2]Planetary Science Institute grinspoon@psi.edu

Introduction: The search for evidence of past oceans on Venus is of fundamental importance for understanding the possible habitability of our nearest planetary neighbor, and the fate of rocky planets around other stars. The search for definitive signs of an ancient ocean is a major goal of the VERITAS, DAVINCI, and EnVision missions to Venus. The Pioneer Venus discovery of the high D/H ratio in Venus' atmosphere implies that at least 1/3 of a terrestrial ocean has been lost from Venus, although this datum is also consistent with the loss of several terrestrial oceans [1]. Alternatively, this value may reflect more recent steady-state evolution in which exospheric escape is balanced with exogenous or endogenous hydrogen sources, obscuring the record of a primordial inventory [2].

Ancient Oceans on Venus?: The existence of oceans on early Venus is only one of two major hypotheses about the history of Venus' water [3]. There are strong theoretical reasons to believe that Venus lost its initial inventory of water while it still had a dense steam atmosphere [4,5]. The existence of oceans on ancient Venus is the other hypothesis, one that is undeniably influenced by a hopeful bias. Ancient oceans could also be reconciled with massive early loss by a late accreting volatile reservoir. Constraining the mineralogy of Venus surface units, such as tessera, recent volcanic outflows, and rift zones is the primary goal of VERITAS' VEM infrared camera. These data are of vital importance to the question of whether the tessera are silicic, and are therefore the remains of ancient continental crust that required surface water to form [6]. Noble gas and light element isotopes (especially C and S) that will be measured by the DAVINCI descent probe will help tell the story of Venus' early atmospheric evolution, and the movement of C and S between major reservoirs.

Atmospheric Mass: If Venus had oceans for geologically long timescales, with continents and a silicate-carbonate cycle, it would not have had the massive atmosphere that we see today. As on Earth, most of the carbon would have been laid down as carbonates at the continent/ocean boundaries. Indeed, if that happened, there were likely massive layers of carbonate deposited in the oceans. If ancient crust is preserved on present-day Venus, it is also possible that the tessera are the crumpled remains of these oceanic carbonate slabs. As [10] points out, volatile recycling would have largely ceased once the oceans disappeared, at which point would start building up in the atmosphere from volcanic outgassing. Without significant sinks for atmospheric, it is possible to estimate the amount of volcanism required to achieve a 90 bar atmosphere during the post-ocean era. [3] analyzed the size and frequency of Large Igneous Province (LIP) emplacements in Earth's history in order to assess the climate impacts of these large scale volcanic events. They concluded that under certain conditions (such as those at Venus), the perturbation to the atmosphere from temporally overlapping LIP formation could be sufficient to lead to a planet's heat death. In Venus' case, leading to the loss of an ocean and subsequent runaway greenhouse effect.

Methods and Significance: We will investigate the scenario of LIP volcanic outgassing, operating for 4 Gy on Venus, to see if it is sufficient to explain the buildup of the current 90 bar atmosphere. Alternatively, if the accumulation of atmosphere began with the loss of oceans 1, 2, or 3 Gya, it may be that the only way Venus could have acquired its present atmosphere is by experiencing a planet-wide resurfacing event, or events, such as the foundering of much of its crust [7]. Our recent theoretical work investigates the transition from a putative water-rich early Venus with Earth-like water clouds to the massive atmosphere with sulfuric acid clouds that we see today. Volcanic sources of CO_2, H_2O, and SO_2 build up in the atmosphere over geologic time, while H_2O is dissociated and is lost to space. Atmospheric CO_2 and SO_2 are permitted to react with surface minerals, an atmospheric sink for these gases. A radiative transfer model with coupled cloud microphysics allows us to identify the atmospheric conditions that were necessary for the transition from water to sulfuric acid clouds. This approach can simulate a large range of volcanic outgassing scenarios, potentially constraining the duration and magnitude of volcanism that is consistent with the current massive atmosphere and its bulk chemical properties. We will also model the evolution of cloud composition and *p*H for a range of outgassing history scenarios, allowing us to investigate whether possibly habitable conditions in the clouds [8,9] would have remained consistent or intermittent over geologic time.

Acknowledgments: MAB and DHG were funded for this work by NASA's Akatsuki Participating Scientist Program

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LUNAR EXPLORATION AS A PROBE OF ANCIENT VENUS. S. H. C. Cabot[1*] and G. Laughlin[1], [1]Yale University (52 Hillhouse, New Haven, CT 06511, USA, *email: sam.cabot@yale.edu)

Introduction: Did Venus at one point harbor Earth-like conditions? Did it host liquid water, and if so, when were its oceans depleted? A high atmospheric D/H ratio suggests that Venus had abundant water [1], but following a runaway greenhouse process, the water was photo-dissociated and subsequently depleted. Currently, there is near-complete uncertainty regarding the details and timeline of the evolutionary path that Venus took. The planet's history remains elusive in the absence of a surface sample; and acquiring such samples pose significant challenges given the present conditions on Venus. We investigate an alternative route to Venusian sample recovery: identification of spalled [2], lightly-shocked ejecta on the Moon originating from a cataclysmic impact on Venus.

Delivery from Venus has not been explored thoroughly in the literature, in part because it has a high escape velocity relative to Mercury and Mars, and lies deeper in the Sun's gravitational potential. Its thick present-day atmosphere is the largest deterrent. Ejecta would have more readily escaped Venus during its posited Earth-like phase. This period may have lasted for only a short while after formation, or it may have extended to as recently as ~0.7 Gya [3]. The Moon lacks geological activity and offers promise to preserve records of ancient impacts on its surface [4]. Importantly, the ongoing resurgence in Lunar exploration (e.g. Artemis) may provide opportunities to locate and identify ancient Venusian meteorites.

Spalled Ejecta: We approximate the quantity and properties of ejecta using the cratering prescriptions of [2]. One may derive the mass m_{ej} ejected for material that experiences shock pressures not exceeding P_{max} [5, 6]. We adopt P_{max} = 40 GPa, beyond which many minerals undergo heavy shock metamorphism or melting. Our nominal calculations involve an asteroid projectile with diameter 8 km, impacting vertically at 30 km s^{-1}. Spall theory predicts $m_{ej} = 3.7 \times 10^{13}$ kg. Based on simulation transfer rates (see below), this mass corresponds to about 680 kg km^{-2} of Venusian material deposited in the Lunar regolith from a single asteroid impact.

Secular and Numerical Evolution of Ejecta Trajectories: Classical second-order secular theory neglects terms in the disturbing function expansion which contain mean longitudes, as they are rapidly varying and average to zero in absence of mean-motion resonances. At this order, time-evolution of eccentricity and inclination is decoupled. [7] published a modified version of this theory that incorporates 10 inclination eigenfrequencies, where the extra two approximately account for the effect of the 5:2 near-commensurability between Jupiter and Saturn. Within this framework, the secular evolution of a massless test particle is deterministic, and is set by its semi-major axis. Particles are assigned residual velocities between 0.0 and 10.0 km s^{-1}. Approximately 30% of ejecta are likely to attain Earth-crossing orbits for these physically plausible initial conditions (Figure 1).

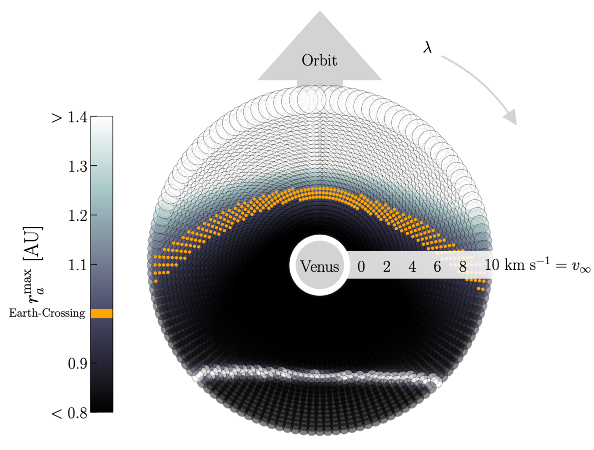

***Fig 1**. Maximum apocenter of particles launched from Venus throughout the course of 10 Myr of secular evolution. Particles which reach 1 AU (orange points) potentially collide with Earth or the Moon. Particles are arranged according to their initial longitude on Venus. Initial semi-major axes range from 0.48 < a < 1.91 AU. No particles launched from the trailing side of Venus can reach Earth for plausible v_∞ except for those in the lightly-shaded band which attain secular resonance with two eccentricity eigenfrequencies.*

We run numerical simulations with the N-body code REBOUND [8] and a hybrid symplectic integrator. We include the Moon as an active particle in the simulation at its present-day separation from Earth. We sample velocities from a distribution corresponding to ejection from the surface by a vertical impact, and repeat for three impact velocities: 25 km s^{-1}, 30 km s^{-1}, and 60 km s^{-1}. We find a Venus-to-Moon transfer rate ranging between 0.01-0.1% over 1 Myr. We adopt a nominal 0.07% for subsequent calculations, which was the transfer rate for the 30 km s^{-1} scenario. Remarkably, Earth acts as a particularly effective attractor and accretes up to 10% of Venusian material. Also, the reciprocal Earth-to-Venus transfer rate is 13%, matching findings of [9].

Ejecta Flux Analysis: Using data from the JPL Small Bodies Database, we find that, on average, asteroids hit Venus with 24% higher speed compared to Earth, and only 13% of Earth collisions exceed twice the escape velocity, whereas 36% of Venus collisions do. We use a Monte-Carlo analysis to estimate the abundance of Venusian material on the Moon, taking into account potential impact and water loss histories. The asteroid impact flux is obtained by integrating the Lunar Sawtooth Bombardment rate of [10], and multiplying it by the ratio of Earth's and the Moon's geometric cross-sections. We randomly sample the duration for which Venus retained water (which we assume is equivalent to the period that it harbored a low-mass atmosphere), and draw asteroid diameters from a truncated power law distribution (positive between $1 - 8$ km).

We obtain a distribution of possible surface densities of Venusian material on the Moon, with median 9.5×10^5 kg km^{-2}. The majority of this material originates from impacts prior to 3.5 Gyr ago. As such, it will not be uniformly mixed into the Lunar regolith. We adopt a simple stratification model to estimate the abundance of Venusian material. It is assumed that impacts prior to 3.5 Gyr ago are mixed within the megaregolith to depths of 1 km, whereas subsequent impacts are mixed within the surface regolith down to 10 meters. The median abundance of lightly-shocked Venusian material in the deep Lunar megaregolith is 0.3 ppm. Assuming the surface regolith probes times later than about 1 Gyr, the median abundance of Venusian material in this layer is 0.2 ppm. The two abundances are similar owing to the fact that, while the post-LHB impact rate is $\sim$100 times lower, it is mixed to depths about the same factor shallower.

We repeated our Monte-Carlo analysis to estimate the abundance of lightly-shocked Earth material on the Moon. Even if Venus lost its water shortly after its formation, we still expect the ratio of lightly shocked Venusian material on the Moon to exceed that of similarly unaltered terrestrial material by a factor of more than two. This conclusion seems robust, as it is determined by fixed variables such as Earth's and Venus' escape velocities, their relative impact flux, and their respective impact velocities; it is independent of the absolute impact flux. If we are able to obtain a collection of Earth and Venus samples on the Moon, the ratio of their abundances may offer some loose constraints on Venus' evolution. The surface regolith profile in Figure 2 allows dating of water-loss times occurring after the end of the Lunar cataclysm. For long-lived oceans on Venus, the V/E abundance ratio saturates at [V/E] ~ 4 in the megaregolith.

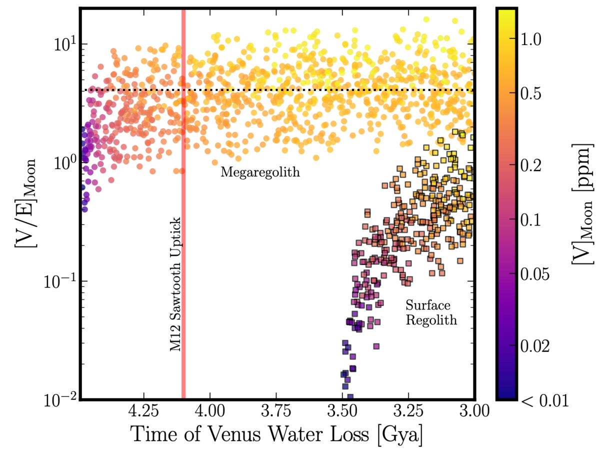

***Fig 2**. Monte-Carlo analysis of the abundance ratio of Venus and Earth material on the surface of the Moon, in both the surface regolith and deeper megaregolith. This distribution is marginalized over impact-related variables to reveal a function of when Venus lost the bulk of its water content. The ratios approach about 4 (black dotted line). The vertical line is located at the bombardment rate uptick [10]. The colorbar indicates the abundance of lightly-shocked Venusian material.*

Identification: Isotopic analyses can eliminate Lunar, Earth and Martian origins of a meteorite displaying terrestrial-like petrology [4, 11, 12]. Venusian material may be located within brecciated Lunar samples, which contain melt and debris from impacts. Triple Oxygen isotope fractionation, metal abundance ratios (e.g. Fe/Mn), and Noble gas abundance ratios (which may be benchmarked against measurements from the forthcoming DAVINCI+ mission) would be most the prudent avenues for identification.

Acknowledgments: We thank an anonymous referee for their constructive comments on our manuscript [13].

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DECIPHERING 4 BILLION YEARS OF GEOLOGICAL HISTORY POTENTIALLY RECORDED IN VENUSIAN TESSERAE. R.E. Ernst[1,2], R. Dean[1], H. El Bilali[1,2], K.L. Buchan[3], [1]Department of Earth Sciences, Carleton University, Ottawa, Ontario, Canada; Richard.Ernst@Carleton.ca; raidendean@cmail.carleton.ca; hafidaelbilali@cunet.carleton.ca, [2]Faculty of Geology and Geography, Tomsk State University, Tomsk, Russia, [3] 273 Fifth Ave., Ottawa, Ontario, Canada; kbuchan33@gmail.com

Introduction: In recent climate models Venus had habitable conditions for much of its history with a Great Climate Transition (GCT) occurring about 700-1000 Ma ago [1-3]. The Great Climate Transition would correspond to a transition from Earth-like conditions to the current hyper-warm surface conditions (450°C, 90 bar atmosphere dominated by 96% CO_2), accompanied by the loss of the surface water cycle and potential end of plate tectonics via the end of subduction of hydrated oceanic crust [3,4].

Tesserae. Tesserae are the stratigraphically oldest units on Venus and cover about 8% of the surface but likely have a more extensive distribution under younger cover (e.g. [5,6]). Tesserae could record evidence of the GCT. This is supported by evidence for erosion exposing subhorizontal layering (of sediment and/or volcanics?) [7] and by the identification of valley morphologies with geometries similar to fluvial systems on Earth [8].

The confirmation of tesserae erosion would suggest that the apparent ca. 700-1000 Ma age of tesserae based on crater counting (e.g. [9]) is anomalously young due to an older record of impacts being removed by erosion. Once the GCT began, erosion would decrease and then cease, and the crater record would start being preserved [8]. From this perspective, tesserae could preserve an ancient geology, back to perhaps even 4 Ga (comparable to Earth).

Nature of this ancient geological history. The geology of tesserae could have similarities to 'basement' rocks on Earth which include a range in lithologies (volcanic belts, sedimentary basins, voluminous granites, layered intrusions, dyke swarms) and are affected by a range of degrees of deformation and metamorphism. Basement rocks on Earth preserve evidence of lateral accretion of terranes. Tessera regions on Venus (e.g. Tellus Regio) appear to also exhibit lateral accretion of terranes [10], an observation that could indicate Venusian plate tectonics preserved in tesserae. The possible presence of felsic magmatism is noted by [11]. The presence of dyke swarms is suggested by [12] who proposed that the ribbon structures, previously characterized as purely structural features [6, 13], should be reinterpreted as graben overlying dykes. So preliminary observations are consistent with an extensive geological history preserved in tesserae.

Deciphering an ancient geological history in tesserae. In anticipation of the upcoming fleet of missions to Venus (VERITAS, DAVINCI from NASA, EnVision from Europe, Venera-D from Russia and Shukrayyan-1 from India), it is timely to develop approaches for the recognition of a potentially extended geological history preserved in tesserae. In the interim, progress in developing such strategies can be made based on existing 100 m / pixel Magellan SAR data.

We consider three aspects for deciphering an extended geological history in tesserae.

1) It is important to recognize features that are late- and post-tessera and are therefore not part of an extended older tesserae history. As an example, detailed mapping of ribbon fabrics and other extensional lineament features in Western Ovda Regio has been interpreted in a dyke swarm context [14]. Some of these inferred dyke swarms cut both the tessera and the adjacent plains (and thus are post tessera and post plains). Others only cut the tessera, but not the surrounding plains, and therefore must be post- or late-tessera, but precede plains volcanism.

Successful identification of such dykes (in late and post-tessera time) will simplify the remaining morphology patterns that can be focused on and considered in the context of a protracted history.

The intra-tessera plains areas (e.g. [5]) need to be assessed as to whether they are products of sedimentary accumulation or volcanic flooding, and if so to identify their sources. These would also represent late-tessera features.

2) A recent model suggests that the GCT was caused by a burst of LIPs volcanism [3]. Specifically, the terrestrial rate of LIPs was applied to Venus, and it was considered that a stochastic pulse of multiple coeval LIPs could have led to a runaway greenhouse effect that caused the GCT. If correct, this model would predict that tesserae would host significant volumes of LIP magmatism. From a terrestrial context we would expect a large amount of subhorizontal flood basalts (although deeper LIP units such as dykes, sills and layered intrusions, could be exposed by erosion).

An insight from Earth is that such LIPs, which cause major climate change, are regional rather than global in extent. For instance, the 252 Ma Siberian Traps LIP, which caused the end Permian mass extinction, only covers about 5 Mkm^2. Three such LIPs would cover only about 15 Mkm^2, which is a small portion of the total global surface area of Venus (460 Mkm^2). Thus, while the LIPs associated with the GCT would be regionally voluminous, they would not be global in extent.

3) Progress toward geological interpretation of tesserae is beginning with morphology mapping of tesserae [15], maps showing variation in backscatter and topography [16], recognition of regions exhibiting potential deep erosion [7] and potential fluvial erosion [8]. It is also important to search for evidence of partially removed impact craters, to determine if crater degradation is due to deformation or erosion, and to develop criteria to recognize such erosion.

The goal of this abstract is to stimulate thinking about a potentially protracted (~4 billion year) geological history being present in tesserae, as a) a focus for the fleet of Venus missions over the next decade and b) a focus for current mapping of tesserae using Magellan images.

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DAVINCI MISSION CONTRIBUTIONS TO ANCIENT VENUS SCIENCE. J. B. Garvin[1], S. A. Getty[1], G. N. Arney[1], N. M. Johnson[1], E. Kohler[1], and the *DAVINCI Science Team*[2]; [1]NASA Goddard, 8800 Greenbelt Road, Greenbelt, MD 20771 (james.b.garvin@nasa.gov), [2]Science team affiliations include NASA JPL, JHU/APL, MSSS, Univ. Michigan, ASU, Wesleyan, LPI, Univ. California at Riverside, NASM/SI, and others (*not all listed here*)

Introduction: NASA's Deep Atmosphere of Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) mission was selected in June 2021 to provide quantitative atmospheric chemistry and environmental boundary conditions for evaluating the divergent pathways of Venus evolution, including the possible role of oceans and hence habitability [1]. Several of the specific measurement-driven investigations associated with the DAVINCI mission and it's *in situ* atmospheric descent probe are tied directly to Planetary & Astrobiology Sciences Decadal Survey priorities that relate to ancient or early Venus [2], including a sampler of them listed in **Table 1**.

As DAVINCI was specifically architected to address questions relevant to the earliest stages of Venus evolution [3], the selected suite of instruments (see [1]) was optimized to provide measurements that advance understanding of early-time processes, e.g., via abundances of noble gases and their isotopic ratios.

Analytical chemistry: The implementation of a deep atmosphere probe with multiple inlets for feeding two analytical chemistry instruments with 10 to 100's of samples is the core of the DAVINCI strategy from ~67 km to the surface, as illustrated in **Figure 1.**

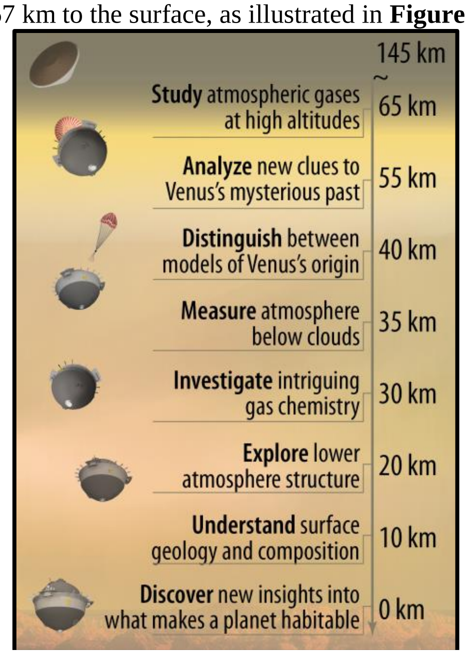

Figure 1: *High-level outline of the specific measurements to be made as part of the scientific transect of the Venus atmosphere [see {1}].*

Synergies: Specific measurements tied to questions pertaining to ancient Venus are summarized in **Table 1,** and further documented in [1].

Connections to VERITAS & EnVision. DAVINCI's measurements of concentrations of trace gases from the primary cloud deck to the surface above the Alpha Regio tesserae (complex ridged terrain) complement the species retrieved by the DLR-developed VEM suite on VERITAS and EnVision orbiters and allow cross-correlation between globally distributed retrievals and *in situ* measured values. In addition, VERITAS global assessment of Fe content in rocks at scales as fine as 50 km will be evaluated at scales finer than 100 m under the clouds by DAVINCI's NIR descent imaging system (VenDI) as potential ground-truth at more scales within one potentially ancient tesserae [1].

Summary: DAVINCI has been optimized to treat multiple key issues associated with ancient Venus from the potential existence and timing of surface oceans to the evolution of Venus' primordial atmosphere. The new measurements of Xe isotopes, of D/H in water throughout the cloud-deck and deep atmosphere and the state of fO_2 near the surface are all significant constraints for improved models of Venus climate evolution. Specific opportunities to extend understanding via isotopes of more challenging nobles such as Helium will be pursued on a best-effort basis, potentially enhancing remote sensing retrievals of trace gases diagnostic of recent volcanism or other processes. Ultimately, DAVINCI will deliver ~ 500 Gbits (uncompressed) of new data about Venus to the PDS and the planetary community from which to pursue studies of atmospheric evolution with implications for exoplanets discovered and evaluated by JWST.

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Additional Information: Please refer to our science-facing DAVINCI *website* for further information and our recently published PSJ paper listed above (as [1]):

https://ssed.gsfc.nasa.gov/davinci

TABLE 1: *Mapping from questions associated with ancient Venus to DAVINCI measurements [1,2]. The DAVINCI payload includes VMS (Venus Mass Spectrometer), VTLS (Venus Tunable Laser Spectrometer), VenDI (Venus Descent Imager), VASI (Venus Atmospheric Structure Investigation), VfOx (Venus Oxygen Fugacity sensor), VISOR (Venus Imaging System for Observational Reconnaissance), and CUVIS (Compact UV-to-Visible Imaging Spectrometer).*

PAS-DS Inner Planet Science Goals	Questions relevant to *Ancient Venus*	Venus Objectives (related to the decade 2023-2032)	DAVINCI	Key Measurements	DAVINCI instruments (see [1])
Understand the Origin and Diversity of Terrestrial Planets (key to Ancient Venus)	Constrain bulk composition of the terrestrial planets to understand formation from the solar nebula and evolution	Understand the physics and chemistry of Venus' atmosphere, abundances of its trace gases, sulfur, light stable isotopes, and noble gas isotopes	**Meets**	Noble gases & isotopes (Xe)	VMS & VTLS
	Characterize planetary surfaces to understand modification by geologic processes	Understand the physics and chemistry of Venus' crust, and its possible evolutionary pathways across time	**Partially Meets**	Composition (surfaces)	VenDI
		Understand weathering environment of the crust of Venus in the context of dynamics of the atmosphere and the composition and texture of surface materials through time	**Meets**	Composition (deep atmos. & surface)	VMS + VenDI + VfOx
Understand How the Evolution of Terrestrial Planets Enables and Limits the Origin and Evolution of Life	Understand the composition and distribution of volatile chemical compounds	Understand the properties of Venus' atmosphere down to the surface and improve our understanding of zonal cloud-level winds (today vs past)	**Partially Meets**	Trace gases, context	VMS & VASI
Understand the Processes that Control Climate on Earth-Like Planets	Determine how solar energy drives atmos. circulation, cloud formation, and chemical cycles that define current climate on terrestrial planets	Constrain the coupling of thermochemical, photochemical, and dynamical processes in Venus's atmosphere and between surface and atmosphere to understand radiative balance, climate, dynamics, and chemical cycles (today as boundary condition for past)	**Meets**	Trace gas composition	VMS, VTLS, VISOR, & CUVIS
	Characterize record of and mechanisms for climate evolution on Venus, with goal of understanding climate change on terrestrial planets, including anthropogenic forcings on Earth	Look for planetary-scale evidence of past hydrological cycles, oceans, and life and for constraints on evolution of the atmosphere of Venus (ancient Venus role of volatiles like water)	**Meets**	Nobles, trace gases, D/H, surface composition	VenDI, VTLS, & VMS
	Constrain ancient climates on Venus and search for clues into early terrestrial planet environments to understand initial conditions and long-term fate of Earth's climate	Links ancient Venus to improved climate models	**Meets**	D/H, Nobles, trace gases, surface composition, oxygen fugacity	VTLS, VMS, VenDI & VfOx

GETTING RID OF VENUS' OCEANS: VOLATILE EXCHANGES ON ANCIENT VENUS. C. Gillmann[1] [1]Rice University, Earth Environmental and Planetary Sciences, MS-126, 6100 Main Street, Houston, TX 77005, USA (cg62@rice.edu).

Introduction: The habitability of a terrestrial planet depends on its surface conditions, which can vary greatly during its evolution. Volatile exchanges between the interior, the surface, and the atmosphere - the cycles of volatile species or their absence - are largely responsible for these variations, and the resulting complex feedback mechanisms between the processes involved. The differences between Earth and Venus climate conditions highlight how similar processes and base characteristics can lead to divergent states after billions of years of evolution. Venus exhibits hostile conditions at present-day, and its atmosphere appears mostly desiccated, but no clear consensus exist on its past evolution, because of the lack of data dating back more than 0.3-1 Ga. While an end-member scenario proposes than Venus may have been desiccated during its magma ocean phase [e.g. 1], some other hypothetical evolution scenarios suggest it was not always dry, and that it could have sustained liquid water oceans for an undefined period of time during its past history [2].

Goals and Methods: We investigate what mechanisms are likely to be responsible for this type of catastrophic change on Venus and possibly on terrestrial planets, using coupled numerical evolution simulations of planetary evolution, involving mantle dynamics, volcanism, atmospheric greenhouse, escape mechanisms, meteoritic impacts, and surface solid-gas exchanges [3]. We consider each mechanism and its possible consequences for the composition of the atmosphere, surface conditions and observables. We run 2D simulations of the evolution of the solid planet, both in long term 4.5 Gyr evolution scenarios and shorter simulations focusing on the consequences of increased surface temperatures as a consequence of runaway greenhouse. One main constraint of the model is that they need to produce present-day conditions compatible with current observation (in terms of atmosphere composition, mainly). We consider the problems each scenario can generate and define under what conditions Venus could have harbored temperate conditions and what sequence of events is required to turn it into its present-day self.

Results: Increasing solar luminosity (the faint young sun paradox) only marginally affects surface temperature changes [2]. Atmospheric escape could only hide the results of a runaway greenhouse phase by removing water rather than cause the observed climate change. Moreover, it is shown, especially in light of recent measurements interpretation [4], to be unlikely to be responsible for massive water loss. Large impacts, capable of releasing large amounts of volatiles in the atmosphere, are infrequent and unlikely to occur during late evolution. Early on, they can be a massive source of volatiles and efficiently desiccate the upper mantle. The smaller impactors do not have enough mass to affect the mantle or atmosphere substantially.

The cause of catastrophic transitions and the means to desiccate the atmosphere of Venus post-runaway greenhouse may be internal [5]. We investigate volcanic gas release based on mantle composition and mantle dynamics over time, as well as oxidation mechanisms of fresh material that can trap volatiles into the surface. Solid surface oxidation is inefficient and, overall, appears to be roughly as efficient (within 0.1-1 order of magnitude) as atmospheric escape, when considering O removal during the last few billion years. It is, however, possibly more efficient during more recent history, when atmospheric escape rates are extremely low. Ashes oxidation could be more efficient but requires explosive volcanism that is not widespread on Venus, given the few traces detected from surface observation. We compare its effects to that on Earth.

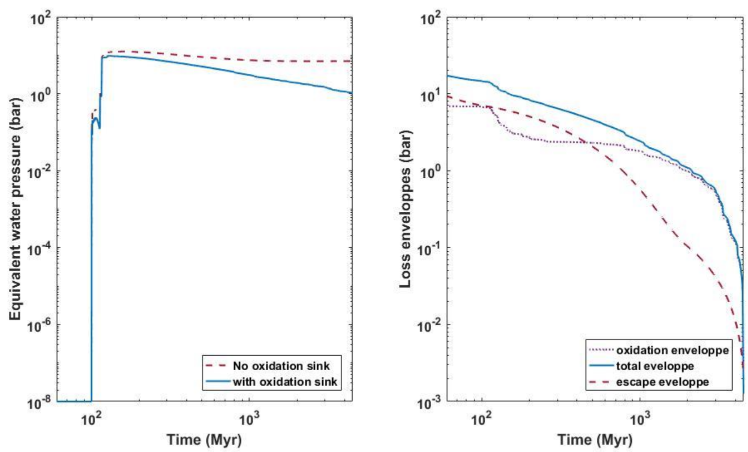

Figure 1: (top) equivalent water content of the atmosphere of Venus with and without surface oxidation sinks. Sources of water are impact delivery and a marginal amount of volcanic outgassing. (bottom) water sinks: maximum amount of water removed from the atmosphere between various times and present-day by escape, surface oxidation and both combined.

Large variations in atmospheric composition and vertical structure resulting from runaway greenhouse could affect all the mechanisms involved in the evolution of terrestrial planets and, with enough water, lead to a late magma surface phase. Surface exchanges and atmospheric loss would therefore be increased, in turn, due to the larger volume of hot molten material available for oxidation at the surface. We investigate this phase by modeling the mantle/lithosphere response to such a runaway greenhouse event.

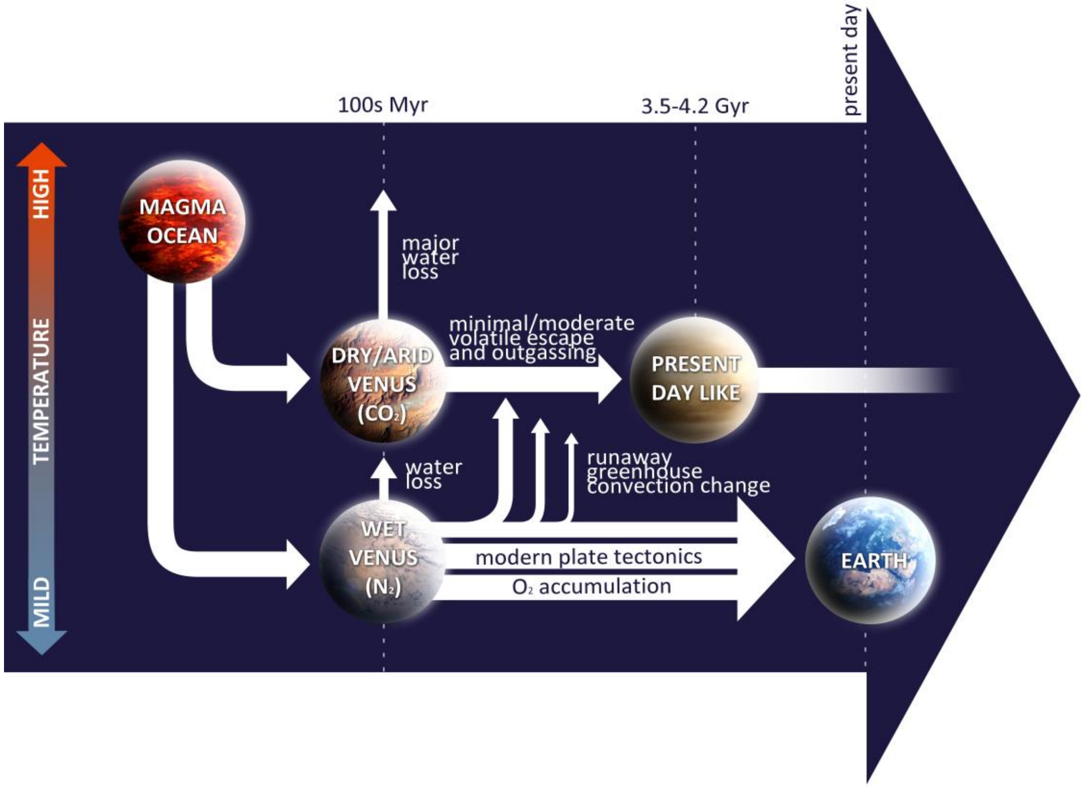

Figure 2: End-member scenarios for the evolution of surface conditions of Venus depending on the fate of water: dry Venus on top, where the planet lost its water early on, during its magma ocean phase; and a more Earth-like wet Venus evolution below, retaining water and milder surface conditions until the climate was destabilized [6].

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THE MINERALOGICAL RECORD OF ANCIENT VENUS CLIMATES PRESERVED IN THE TESSERAE.
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Introduction: Venus tesserae are consistently stratigraphically older than the plains with a crater age 1 to 1.4x the global average of 0.5 – 1 Gy [1,2,3]. The lack of widespread deformed craters or crater-like features within the tesserae shows that this age is certainly the last deformation age, but there are no constraints on the formation age of tessera materials. As such, the Venus tesserae are likely our only record of an earlier period in the history of the planet. Determination of specific rock types in the tesserae would provide critical insights into an early period of Venus' history. The VIRTIS data show that tesserae have a lower ~1μm emissivity than the plains, which we interpret to indicate that the tesserae have a lower FeO content [4,5]. Gilmore et al. [6] considered several possible histories for tessera terrain that relate to Venus's climate evolution and could produce this emissivity signature. These histories are testable using orbital NIR spectroscopy if the emissivity signatures of minerals subject to Venus conditions are known.

Mineralogical signature of early wet climates: If we assume that Venus and Earth had similar volatile inventories at the outset as is suggested by models for accretion [e.g., 7], the high D/H ratio of the venusian atmosphere [8,9,10] is consistent with the loss of a significant inventory of water over the history of the planet. There is debate about the volume and rate and mechanisms of water loss, yielding estimates of the lifetime of a Venus ocean that range from 600 Ma [11] to ~2 Ga [12] or ~3 Ga [13]. The presence of liquid water, along with a plate recycling mechanism, would allow formation of large quantities of evolved, high silica melts [35] and primary hydrous precipitates such as evaporites. These rocks would be subject to weathering in a wet climate. The primary and weathered phases from the wet climate would then again be altered in the modern greenhouse climate (Fig. 1).

Hypothesis 1. The tesserae contain felsic rocks formed and/or weathered in a water-rich climate. Recently published NIR emissivity spectra of felsic and mafic rocks [14] confirm and quantify the prediction from room temperature spectra that felsic rocks at Venus temperatures have distinctly lower values of emissivity and can be readily distinguished from mafic rocks in orbital data. The formation of significant volumes (continents' worth) of granitoid magmas can occur via several mechanisms, each of which require both water and a plate recycling mechanism for formation [35]. In any case, if all tesserae are confirmed to be felsic, that ties their formation to an earlier era when Venus had an active hydrologic cycle. This is suggested also by recent studies of tessera morphology that identify layered sequences in the tesserae [15], and topographic features consistent with drainage basins [16]. Felsic rocks dominated by felspars, quartz and with biotite and minor Fe-oxides would have weathered in a hydrous environment, producing phyllosilicates and oxides. These minerals would then be exposed to the modern climate. Hydrated phyllosilicates are not stable under current surface conditions of high temperatures and low water content and are predicted to break down via dehydration, oxidation and/or sulfatization [17,18].

Hypothesis 2a. The tesserae contain mafic rocks formed and/or weathered in a water-rich climate. It is also possible that the tesserae comprise basalts

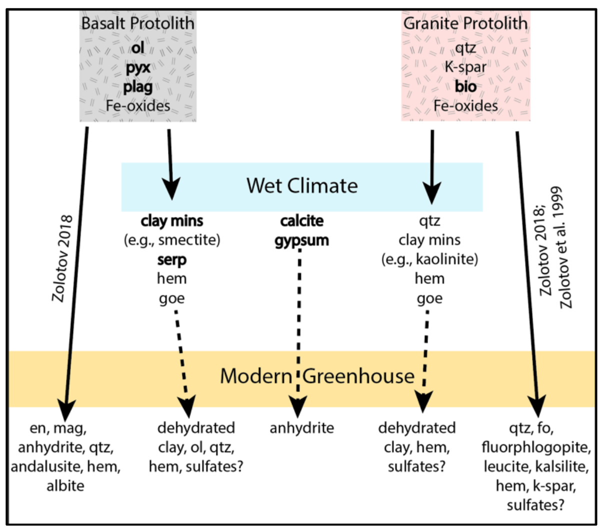

Figure 1: Potential weathering processes on Venus. Arrows with references are derived from equations 6 and 8 of [19] and equations 4, 6, 7, 8, 9, 11, 12 from [20]. ol-olivine, pyx-pyroxene, plag-plagioclase, serp-serpentine, hem-hematite, goe-goethite, qtz-quartz, K-spar-potassium feldspar, bio-biotite, en-enstatite, mag-magnetite, fo-forsterite.

weathered on an ancient Venus with an active hydrological cycle. Basalts are expected to weather to ferric oxides, phyllosilicates such as smectites and chlorites and potentially amphiboles [e.g., 21,22]. The spectra of phyllosilicate minerals that lack ferrous iron are dominated by vibrational features in the infrared and have high reflectance (low emissivity) at 1 μm [e.g., 23]. Again, hydrated phyllosilicates are predicted to break down via dehydration, oxidation and/or sulfatization. The smectites saponite and montmorillonite retained high reflectance values at 1 µm even when dehydrated to and beyond present-day Venus temperatures [24,25], a signature which may correspond to low emissivity.

Hypothesis 2b. The tesserae contain mafic rocks formed and/or weathered during plains emplacement. The stratigraphic position of the tesserae suggests that they were present prior to and during the eruption of the plains lavas. Volcanic outgassing, such as that predicted by catastrophic models of plains formation, is expected to release copious amounts of water and SO_2 allowing the weathering of basalts under a higher P_{H2O} regime where in the top 10s of microns, all Fe is converted to hematite and all pyroxene and plagioclase is converted to anhydrite. Basalts weathered under SO_2-rich volcanic gases alter to amorphous silica and sulfates, which have high 1 µm reflectance in spectra collected under terrestrial conditions [26,27,28]. Massive volcanic outgassing has been modeled to lead to cloud formation and a temporary reduction in surface temperatures [29], which should favor the production of carbonates via the weathering of Ca and Mg silicates [30]. Such carbonates are predicted to react with the present-day atmosphere to form sulfate minerals [31, 17] with high 1 µm reflectance [28].

Hypothesis 3. Primary aqueous minerals. A terrestrial planet with an active hydrological cycle could produce primary aqueous minerals such as carbonates, sulfates and other evaporites. Carbonates are not stable on modern Venus and are expected to convert quickly to anhydrite [19, 31, 20]. Both carbonates and sulfates have high 1 µm reflectivity which should correspond to low emissivity.

Mineralogical signature under the modern greenhouse climate: *Hypothesis 4. The tesserae contain felsic rocks formed and weathered in a greenhouse climate.* The expected products of the weathering of major rock-forming minerals are provided in [20] which is an extensive review of the literature of expected weathering of minerals under present-day Venus conditions predicted by equilibrium chemical thermodynamics and laboratory experiments. All iron bearing minerals are predicted to oxidize at modern f_{O2} values, producing ferric oxides and removing ferrous iron in the original rocks. Similarly, Ca in minerals is expected to react with atmospheric sulfur to produce sulfates. Felsic rocks are expected to decompose to an assemblage of quartz and Al-rich phases such as kalsilite and leucite; orthoclase is expected to convert to the Mg, F, K rich fluorophlogopite [32].

Hypothesis 5. The tesserae contain mafic rocks formed and weathered in a greenhouse climate. As summarized in [20] the reaction of Fe^{2+} and Ca in mafic phases is thermodynamically predicted to yield more Mg-rich phases such as enstatite, Al -rich phases such as andalusite, sulfates and oxides. These reactions have been observed experimentally [e.g., 33] The production of iron-free secondary minerals such as anhydrite, or Fe^{3+}-bearing minerals such as magnetite and hematite will reduce 1 µm emissivity signature of weathered mafic rocks, an effect that has been invoked to interpret the VIRTIS emissivity of volcanic flows [34].

Summary. We have described several possible scenarios for the weathering of Venus tessera terrain over time. The type (wet climate vs dry) and timing of the formation and weathering of primary melts (felsic vs mafic) is predicted to create distinct mineral assemblages that may allow us to test each hypothesis and determine the composition of the tesserae and its climate history. Key to this methodology is 1) experimental data examining the reactions of hydrous phases, including clays, under modern Venus conditions and 2) measurement of their ~1 µm emissivity at Venus temperatures.

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THE ORIGIN OF VENUS' ATMOSPHERE: GEOLOGICALLY RECENT OR ANCIENT (FOSSIL)?

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The nature of the geologically recent runaway greenhouse Venus atmosphere, its relation to Venus geologic and geodynamic history, and why it is so different from that of the Earth, are all questions that have perplexed planetary scientists since the early Space Age [1]. A number of recent studies have focused on *forward-modeling* of the origin and evolution of the Venus atmosphere with the current atmosphere as the end-product, defining and assessing the nature and abundance of volatiles derived from the interior and from space, their influence on the atmosphere and interaction with the surface, and the rates of their loss to space [2-4]. Several *forward models* have found that more Earth-like clement conditions [2], with oceans and an N_2-dominant atmosphere [3-4], may have existed into the last ~20% of the history of Venus (Fig. 1), the age of the oldest observed geologic units [5], the tesserae [6], and the global volcanic plains that followed [7].

Critical to the assessment of these models is the role of volcanism, the primary process of transfer of volatiles from the Venus mantle to the surface and atmosphere. In this study, we use the current atmosphere as a baseline and work *backward* in time, assessing the nature and magnitude of the major phases of volcanism revealed in the geological record [5], their style and magnitude of volatile output [7], and the candidate effects of their volatile release on the observed atmosphere. The atmospheric pressure of the current Venus atmosphere (93 bars) is sufficient to significantly inhibit the exsolution of key volatile species during effusive eruptions [8-9] and to preclude explosive volcanic activity that could deliver exsolved volatiles high into the atmosphere, except in extreme cases where the volatile content exceeds several wt% [9].

We specifically address the following questions: 1. Does the eruption of the *total volume of extrusive deposits observed on Venus contribute significantly* to the current atmosphere? 2. How does the volume of the most recent phase of volcanism (lobate plains; large shield volcanoes) affect the interpretation that observed atmosphere SO_2 levels are related to current ongoing volcanism? 3. Could the period of near-global volcanic resurfacing (psh, $rp_{1,2}$) have *produced* the current atmosphere? 4. Do the characteristics of the oldest units (tesserae) shed any light on whether the current atmosphere largely predates the observed geologic record (dating from sometime in the first 80% of Venus history) or was produced during the last 20% of the history of Venus? Addressing these questions provides a framework on which to define the array of evolutionary pathways that Venus and Earth might have followed, refine further the future questions and approaches to the exploration of Venus, and assist in the interpretation of the dozens of new Venus-like exoplanets.

The Magellan mission provided global image coverage that enabled identification of geologic units and their stratigraphic relationships, the construction of a global geologic map [5], assessments of the nature and role of volcanism [7] and tectonism [10] with time, and estimates of the absolute timescale of these events [13]. The observed geological record provides an estimate of the nature of volcanic units, their areal coverage, their stratigraphic relationships and thicknesses, and estimates of the time scale of their emplacement. A summary of the key data for volcanism is presented in [7], their Fig. 26 and Table 5, reproduced as Table 1 here.

We converted the volumes of the main volcanic units [7; Table 1] to lava/magma masses using a density of 3000 kg m^{-3}. Next, we chose the *upper* value where there is a choice of 2 possible thicknesses, and added the contributions from *all* of the units ("total eruptives" in Table 1); summing the values of the 3 "total eruptives" gives the absolute upper limit estimate of the mass of documented volcanics that could contribute to the atmosphere, 7.335×10^{20} kg. The current mass of the Venus atmosphere is 4.8×10^{20} kg. Therefore in order to make the current atmosphere from the above volcanics, *the magma would have to consist of 65.4% by mass volatiles*, which is, of course, impossible. We conclude that the *grand total* of the currently documented volcanics can not have produced other than a very small fraction of the current atmosphere.

Exsolution of volatiles during volcanic eruptions is significantly dependent on surface atmospheric pressure [8-9]. As a specific example, we next looked at the contributions of SO_2 to the current atmosphere. The current SO_2 content of the 4.8×10^{20} kg atmosphere is 150 ppm, so there is a mass of 7.2×10^{16} kg in the atmosphere. Gaillard and Scaillet [3; their Fig. 3] shows that the amount of S released from their typical basalt, even if it is decompressed to the lowest Venus surface pressure, 40 bars in the highest terrains, is only ~1.6% of the assumed inventory, 1000 ppm, i.e., 16 ppm of S. SO_2 has a molecular mass of 64, double that of S, so this represents 32 ppm of SO_2. The total erupted volcanic mass is 7.335×10^{20} kg; 32 ppm of that is 2.35×10^{16} kg. In summary, the *total mass of all volcanics* could have released 2.35×10^{16} kg of the current 7.2×10^{16} kg, i.e. 32.6% of the current SO_2 in the atmosphere. Taking only the recent volcanism total amount (pl, 1.365×10^{20} kg) shows that this is only 18.6% of the grand total. We conclude that it is highly unlikely that a significant amount of SO_2 is being constantly supplied to the atmosphere by recent volcanic activity, particularly in the period of eruption of pl emplacement, representing the vast majority of the total observed geological record.

Discussion and Conclusions: On the basis of these data and simple calculations we present the following findings and explore their implications for the climate history of Venus:

1. The current high atmospheric pressure severely inhibits the degassing of mantle-derived S, H_2O and CO_2 brought to the surface by volcanism and its contribution to the atmosphere [8-9].

2. The current high atmospheric pressure severely inhibits plinian explosive eruptions that can deliver volatiles directly into the atmosphere on Earth and in Mars-like low-atmosphere density environments [9].

3. The *total volume* of lava erupted in the stratigraphically youngest period of the observed record (pl, rift-related, volcanic edifices) is insufficient to account for the current abundance of SO_2 in the atmosphere; thus, it seems highly unlikely that current and recently ongoing volcanism could be maintaining the currently observed 'elevated' levels of SO_2 in the atmosphere [11].

4. The *total volume* of lava erupted in the period of *global volcanic resurfacing* (psh, rp_1, rp_2) is insufficient to produce the CO_2 atmosphere observed today, even if the ambient atmospheric pressure at that time was only 50% of what it is today. Therefore, a very significant part of the current CO_2 atmosphere must have been inherited from a time prior to the observed geologic record, sometime in the first ~80% of Venus history.

5. The amount of water degassed to the atmosphere during the period of *global volcanic resurfacing* would have been minimal, even if the atmospheric pressure was only 10% of what it is today. Therefore, the current low atmospheric water content may be an inherent characteristic of the ambient atmosphere and not necessarily require enhanced loss rates to space in at least the last 20% of Venus history.

6. Because of the fundamental effect of atmospheric pressure on the quantity of volatiles that will be degassed, varying the nature of the mantle melts over a wide range of magma compositions and mantle fO_2 has minimal influence on the above conclusions.

7. If the period of *global volcanic resurfacing* was insufficient to produce the current atmosphere, then it seems unlikely that the immediately preceding period of tessera deformation could have occurred in the presence of a more clement, Earth-like atmosphere and climate with an active surface water cycle [12]. Higher resolution documentation of any types of atmospheric erosion patterns in the tessera terrain will be a critical test.

8. The current atmosphere may be a "fossil atmosphere", largely inherited from a previous epoch in Venus history; if so, it may provide key insights into the conditions during the first 80% of Venus history [e.g., 16].

9. If episodic periods of *global volcanic resurfacing* (such as seen in the observed recent geologic record) were responsible for building up the "fossil atmosphere", then assuming an initial 1 bar atmosphere, more than 90 similar *global volcanic resurfacing periods* would be required to produce the currently observed CO_2 atmosphere.

10. A critical question is: What was the atmospheric pressure/water content/solar insolation 'tipping point' that led to the general stabilization of this "fossil atmosphere"?

On the basis of these preliminary conclusions, we are now exploring 1) volatile contributions with time, using the range of estimates for volumes [7], the several suggested time-scales for the observed geologic record [13], and the pressure-dependence of volatile exsolution and speciation [8], 2) an updated model for the ascent and eruption of magma under different surface pressures, using the lunar end-member as a baseline [14], 3) a wider range of mantle compositions and fO_2 [15], 4) a wider range of candidate fluxes in individual eruptions, 5) improving the definition of parameter space for the occurrence and nature of explosive eruptions and the nature, interaction and dispersal of volatiles and tephra, and 6) assessing the predictions of these sets of results for the fate of the volatile species that are produced during eruptions (interaction with both the surface [15] and existing atmosphere).

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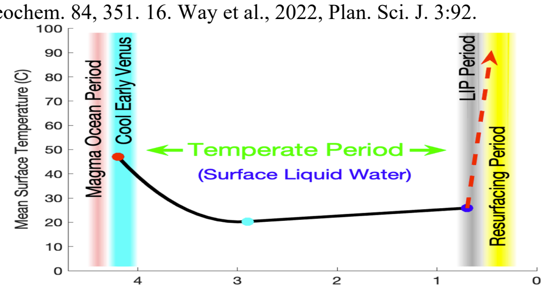

Fig. 1. Possible climate history (Way and Del Genio, 2020).

Unit	Exposed Area ($10^6 km^2$)	Max Area ($10^6 km^2$)	Mass (10^{20} kg) at specific thickness (km)					
			0.1	0.2	0.3	0.4	0.5	N/A
psh	84.5	320.3	0.96	1.92				
rp1	150.7	235.8				2.82	3.54	
rp2	44.8	85.1	0.27	0.51				
pl (lobate plains)	40.3	40.3			0.36		0.60	
pl (large volcanoes)[a]								0.255
pl (large volcanoes)[b]								0.51
total eruptives				2.43			4.14	0.765

total eruptives from all 3 contributions: 7.335×10^{20} kg

Table 1. Estimates of masses of volcanics from stated volcanic sourc

FUNDAMENTAL QUESTIONS ABOUT 'ANCIENT VENUS' REVEALED BY GLOBAL GEOLOGICAL MAPPING: IDENTIFICATION OF FUTURE CHALLENGES AND OPPORTUNITIES. Mikhail A. Ivanov[1,2] and James W. Head[2], [1]Vernadsky Institute of Geochemistry and Analytical Chemistry, Moscow, Russia, [2]Department of Earth, Environmental and Planetary Science, Brown University, Providence, RI 02912 USA (mikhail_ivanov@brown.edu; james_head@brown.edu).

Introduction and Background: A global geologic map of Venus was compiled [1] at a scale of 1:10 M, using Magellan radar image and altimetry data, supplemented by Venera-15/16 radar images. The map (Fig. 1) covers the entire surface of Venus (460 10^6 km^2), 90% of the surface area of Earth. The associated documentation [1] outlined the history of Earth and planetary geological mapping to illustrate the importance of utilizing the dual stratigraphic classification approach to geological mapping. On the basis of this well-established approach, thirteen distinctive units and a series of structures and related features were identified on the surface of Venus. Included were discussions of 1) the history and evolution of the definition and characterization of these units, 2) exploration and assessment of alternative methods and approaches that have been suggested, and 3) an outline of the pathway from the sequence of mapping of small areas, to regional and global scales. As seen in Fig. 1, the contribution outlined the specific definition and characterization of these units, mapped their distribution, and assessed their stratigraphic relationships.

On the basis of these data, [1] then compared local and regional stratigraphic columns and compiled a global stratigraphic column, defining rock-stratigraphic units, time-stratigraphic units, and geological time units. Superposed craters, stratigraphic relationships and impact crater parabola degradation were used to assess the geologic time represented by the global stratigraphic column. On the basis of these data and the unit characteristics, [1] interpreted the geological processes that were responsible for their formation, and then, on the basis of unit superposition and stratigraphic relationships, interpreted the sequence of events and processes recorded in the global stratigraphic column.

The earliest part of the history of Venus (Pre-Fortunian) predates the observed surface geological features and units. Although remnants may exist in the form of deformed rocks, the upper stratigraphic limit of the pre-Fortunian Period is undefined. The observable geological history of Venus was subdivided into three distinctive phases (Fig. 1). The earlier phase (Fortunian Period, its lower stratigraphic boundary cannot be determined with the available data sets) involved intense deformation and building of regions of thicker crust (tessera). This was followed by the Guineverian Period. Distributed deformed plains, mountain belts, and regional interconnected groove belts characterize the first part and the vast majority of coronae began to form during this time. The second part of the Guineverian Period involved global emplacement of vast and mildly deformed plains of volcanic origin. A period of global wrinkle ridge formation largely followed the emplacement of these plains. The third phase (Atlian Period) involved the formation of prominent rift zones and fields of lava flows unmodified by wrinkle ridges, often associated with large shield volcanoes and, in places, with earlier-formed coronae. Atlian volcanism may continue to the present. About 70% of the exposed surface of Venus was resurfaced during the Guineverian Period and only about 16% during the Atlian Period. Estimates of absolute model ages (Fig. 1) [2] suggest that the Atlian Period was about twice as long as the Guineverian and, thus, characterized by significantly reduced rates of volcanism and tectonism. The three major phases of activity documented in the global stratigraphy and geological map [1], and their interpreted temporal relations [1,2], provide a basis for assessing the geological, atmospheric and geodynamical processes operating earlier in 'Ancient Venus' history [e.g., 3-5] that led to the preserved record [1]. In addition, detailed analysis of the preserved volcanic [6] and tectonic [7] records permit a more in-depth understanding of the geologically recent history, the associated geological processes [8-10] and the major unknowns and outstanding questions. Below we list some of compelling questions and challenges for future Venus research (see also [11]).

Some Fundamental Outstanding Questions:

1. Is there evidence for extensive pyroclastic activity? When, where and how abundant?: This is critically important to constrain the history of the present atmosphere and links to the potential volatile content of eruptive magmas.

2. What is the relationship of coronae, novae, arachnoids, and shield volcanoes in space, time and altitude?: Are these features related in origin, space and time? This is a critical question to assess the nature and evolution of mantle dynamics (e.g., mantle plumes, broader mantle upwellings, etc.) and how this might have changed with time.

3. What constraints does the distribution and volume of volcanic plains of different ages place on the origin and evolution of the atmosphere?: Estimates of the areal coverage, embayment relationships, thickness, and volumes of units of extrusive volcanic origin is key to assessing the input of magmatic volatiles into the atmosphere.

4. How does the current atmospheric environment influence the ascent and eruption of magma?: Clearly, the very high Venus atmospheric pressure inhibits magmatic gas exsolution, concentration and explosive volcanic eruptions. Is there any evidence for widespread pyroclastic deposit in the past and could such deposits signal the presence of a very different, lower-atmospheric-pressure environment?

5. What is nature and relationships of festoons and pancake domes?: Are they silica-rich volcanism, viscous magmatic foams, or both? How do they differ in terms of their age and geologic setting?

6. How do tessera patterns of deformation compare among the different occurrences and how do similarities and differences inform us about tessera origin (e.g., lateral collision, upwelling, downwelling etc.)?: In order to span the gap between the preserved geologic record (e.g., [1]) and the earlier, more ancient "cryptic" history, this question requires detailed and comprehensive geologic mapping and modeling studies.

7. How much strain is represented by deformational features in the tessera, and how does this vary in space and time?: These are critical issues in understanding ancient "cryptic" Venus history and the transition to the current record (see details in [10]). Detailed geologic mapping of deformation features in the tessera and integrations across different tessera occurrences is essential.

8. What is the history of topography on Venus and how does this inform us about the Venus thermal and geodynamic evolution?: When and how did the current topography form? What are the relative roles of Pratt and Airy isostasy, and dynamic support? How can theory, observations (geologic mapping and topography) address this question?

9. What are the criteria for recognizing tectonically modified impact craters in the tessera and can additional craters be recognized?: Which tessera elements represent more ancient terrain dating back into the "cryptic" period of Venus history? Can we develop additional criteria for recognizing tectonically and volcanically modified craters and comprehensively map the tessera in search for any evidence of these?

10. What are the relationships of gravity highs and recent volcanism?: Where on Venus is the most likely recent geological deformation and volcanism [12]? How do these relate to the several positive gravity anomalies suggesting active mantle upwelling?

11. How can we distinguish between tectonic and volcanic features and processes?: Graben and fractures of tectonic origin abound on Venus, but some are radial and concentric to coronae, and related central volcanic features. How many of these are due to near-surface dikes of volcanic origin? Which have associated pits, domes and flows?

12. What is the relationship between rift zones and the major lobate flows that originate there?: Detailed documentation of the relationships (time and space) is essential to understand the global rifting system and implications for mantle convective patterns.

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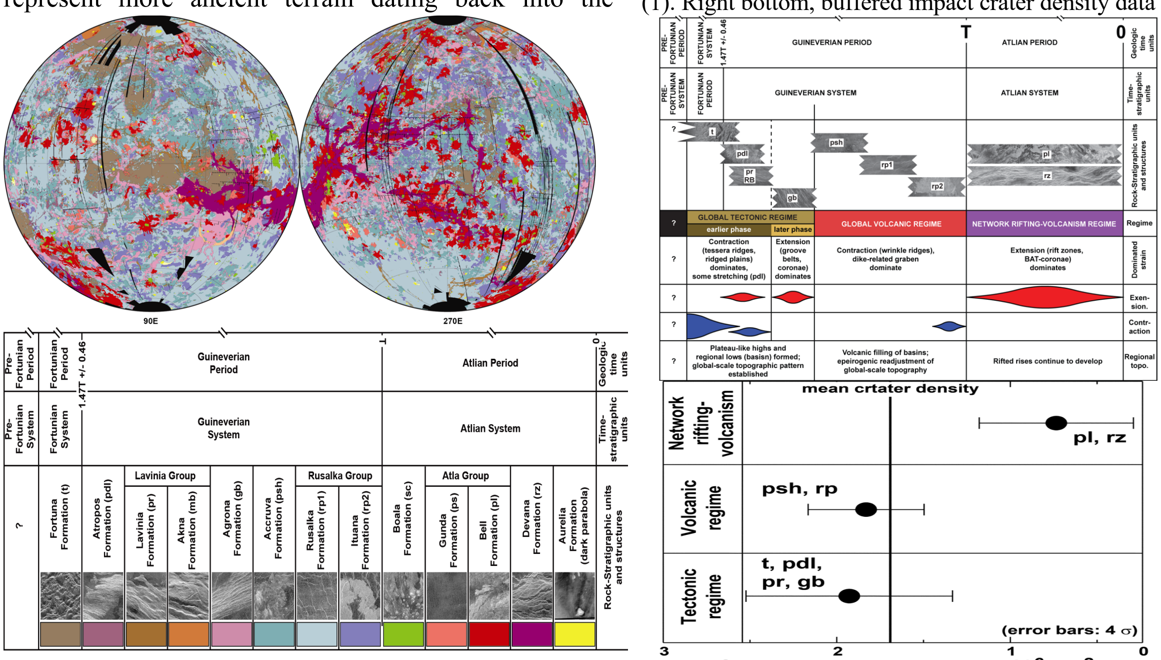
Fig. 1. Left top, geologic map; bottom left, stratigraphic column; Right top, interpreted 3 phases of geologic evolution and events (1). Right bottom, buffered impact crater density data (2).



What does it mean to have no Moon? Evidence for an early or no giant impact on Venus. S. A. Jacobson[1] and C. Dobson[1], [1]Michigan State University (seth@msu.edu).

Introduction: Terrestrial moons come from giant impacts. The moons of Earth and Mars are most consistent with hypotheses of giant impacts [1-13]. Not only are all extant terrestrial moons consistent with giant impacts, but numerical simulations of giant impacts between terrestrial planetary embryos create circumplanetary disks with near ubiquity (>90% of cases with the remaining cases likely just under-resolved) [14]. These circumplanetary disks will spread to create regular moons [15]. Thus, terrestrial moon formation is a direct consequence of giant impacts between planetary embryos. If a giant impact occurred on Venus, then we would expect Venus to have a Moon.

Diverse modern theories of terrestrial planet formation run the entire gamut of giant impact frequencies from very few to very many. Perhaps, Venus never suffered a giant impact, and in some models this is hypothesized [16]. However, it seems unlikely that two of the terrestrial planets would suffer giant impacts and two would not. However, tiant impacts are not the only interactions between planetary embryos in the terrestrial planet-forming disk. Throughout the lifetime of the disk, planetary objects are flying by each other during close gravitational encounters.

Role of planetary flybys in terrestrial moon loss: In typical planet formation simulations, Venus-like planets naturally accrete only about a Venus-mass of material, however these planets will interact with approximately two orders-of-magnitude more mass during planetary flyby events [17]. During these flybys, gravitational torques act on whatever objects are in orbit about Venus.

We are not the first to examine the role of flybys on the dynamical evolution of terrestrial moons. Leftover planetesimals from the terrestrial planet-forming disk crashed onto Earth after the Moon-forming impact. 0.5% of an Earth mass of planetesimals accreted onto Earth to create the late veneer highly siderophile element record, but a much higher mass of material flew by the Earth-Moon system torquing it. The Earth's Moon is inclined by about 5° today, which due to tidal evolution was about 10° initially. This orbital tilt is naturally explained from those flyby interactions [18].

Numerical modeling of collisionless encounters: We modeled the evolution of moons formed after the last giant impacts in terrestrial planet formation simulations. After a giant impact, we estimated the size of the moon from numerical simulations [14,19] and placed it at the Roche radius. We then integrated the moon's dynamical evolution due to tidal interactions with the planet, assuming a range of tidal parameters for different case studies. This smooth tidal evolution was interrupted whenever a close encounter occurred during the terrestrial planet formation simulation. We used a four-body integrator (Sun, Venus, moon, flyby planetesimal) to model the gravitational perturbation from the collisionless encounter. We repeated this process alternating between tidal evolution and collisionless encounters until the simulation contained no more planetary flybys.

Results: We find that collisionless encounters are more effective at removing moons when the last giant impact occurs early as opposed to late in the accretion history of a terrestrial planet. Lunar orbits are progressively excited by planetary flybys increasing their eccentricities and inclinations. Tidal relaxation does decrease excitation, but this process is typically not efficient once the orbit becomes large. Moons are lost as they are placed on near-parabolic escape trajectories and go into heliocentric orbit. We did not track the final fate of these moons, but some fraction may come back to impact the Venus analog.

Discussion: Prior work showed that Venus and Earth could have significantly different accretion histories within the same terrestrial planet formation simulation [19]. This raises the significant possibility that the lack of a Venusian moon is not due to a lack of giant impacts but a lack of a late giant impact. The lack of a late giant impact has significant consequences for the evolution of Venus, and it is a testable hypothesis.

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VENUS'S MANTLE: KEY FOR CHARACTERIZING ANCIENT SURFACE MOBILITY. Peter James[1], Scott King[2], [1]Department of Geosciences, Baylor University (P_James@baylor.edu), [2]Department of Geosciences, Virginia Tech.

Background. Due to the relative youth of Venus's surface, much of its tectonic history has been obscured. Photogeologic studies of Venus's ancient tectonic deformation are generally limited to the relatively small portions of the surface that most plausibly preserve structures older than 500 My (e.g., tesserae) [1]. We argue here that more extensive records of ancient Venus are in fact preserved beneath the surface.

Formation of a depleted cratonic lithosphere on the Archean Earth. Partial melting of the Earth's mantle generally leaves behind a depleted residuum with a lower Mg-number and with a density lower than that of primitive mantle. This depleted residuum generally resides in the upper mantle and can be redistributed through tractions associated with mantle convection (Fig. 1). Large accumulations of residuum form the cores of continental cratons. These sub-cratonic lithospheres are rigid—with a higher yield strength than that of the crust—and have persisted for billions of years. Due to this relative mechanical strength, the supercontinent cycle on Earth may be thought of as a cycle of sub-cratonic lithosphere migration, in which continental crust is simply along for the ride [2].

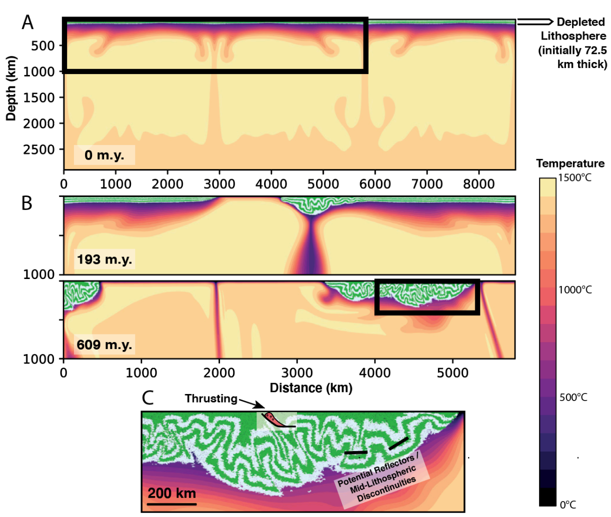

Figure 1: Simulation of the redistribution of buoyant, depleted mantle (green) [3]

Mass anomalies in Venus's mantle: some are plumes, but some may not be. A characterization of Venus's mantle structure was enabled by the Magellan mission, which yielded nearly global maps of gravity anomalies and topographic shape. A two-layered model that simultaneously minimizes gravity residuals and non-isostatic stress results in a map of mass anomalies in the mantle (Fig. 2). This map reveals a suite of buoyant upwellings that are surrounded by modest, interconnected downwellings. Thermal convection can produce hot mantle plumes, and the buoyancy associated with thermal expansion can explain many of the features in Fig. 2. However, mass anomalies can alternatively be produced by compositional variations.

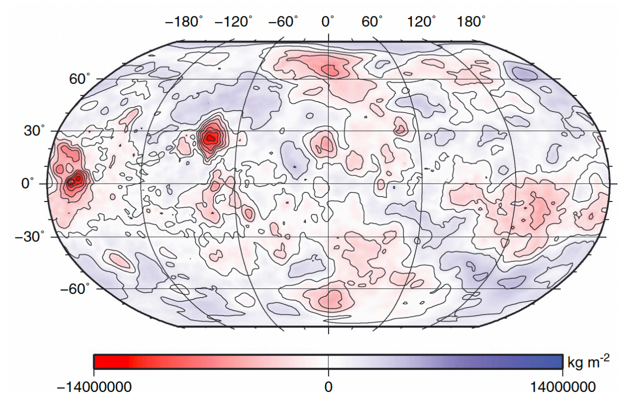

Figure 2: Mass anomalies in the mantle inferred from Magellan data [4]. **Red** regions indicate upwardly buoyant mantle and low density; **blue** regions indicate negative buoyancy and high density.

Cratonic lithosphere on Earth is not substantially buoyant, but this may be due to thermal differences between Earth and Venus. Continental cratons on Earth are relatively cool, which counteracts the positive buoyancy associated with the depleted composition (Jordan's "isopycnic hypothesis" [5]) and may in fact yield a net negative buoyancy [6]. In contrast, the buoyancy of Venus's mantle could be explained if residuum is not significantly cooler than normal mantle at comparable depths. This could possibly explain the large negative mass anomaly under Ishtar Terra (Fig. 2), since Ishtar is not commonly thought to be underlain by a mantle plume.

Implications for plate-like deformation on ancient Venus. The mechanical rigidity of depleted cratons may influence the localization of tectonic strain on a planet. Fig. 1 demonstrates that once a depleted craton has formed (e.g., the craton above the downwelling at 193 My), it preserves its form even through lateral translation (as seen to the left of the black box at 609 My). Even in a regime that is not particularly mobile, tectonic deformation will be concentrated in regions of the lithosphere with lower yield strength.

The influence of cratonic strength may be apparent on western Ishtar Terra (Fig. 3). At the core of western Ishtar lies Lakshmi Planum: a relatively undeformed plain that is surrounded by high-elevation fold and thrust belts. These belts exhibit large amounts of strain that contributed to a thickening of the crust. If Lakshmi was underlain by an early accumulation of residuum, this could have inhibited subsequent strain and concentrated later strain around the periphery (Fig. 4)

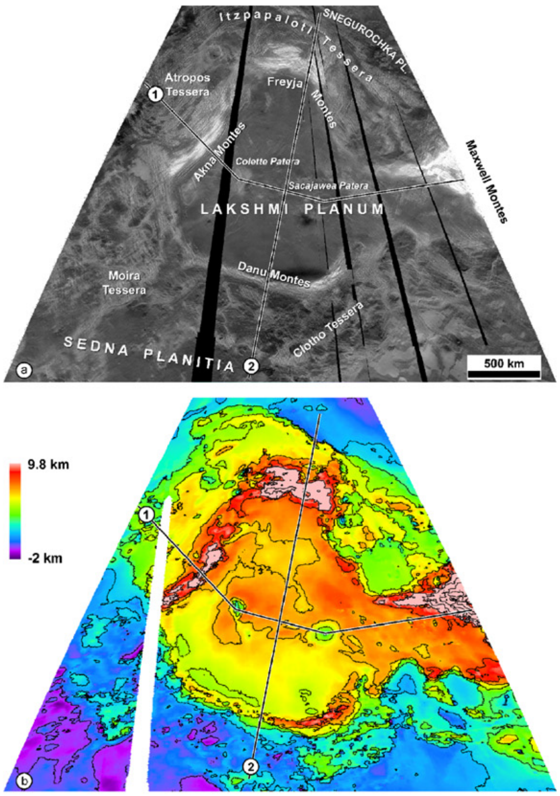

Figure 3: Major morphologic (a) and topographic (b) features of Lakshmi Planum, including high-elevation ridges surrounding the periphery. [7]

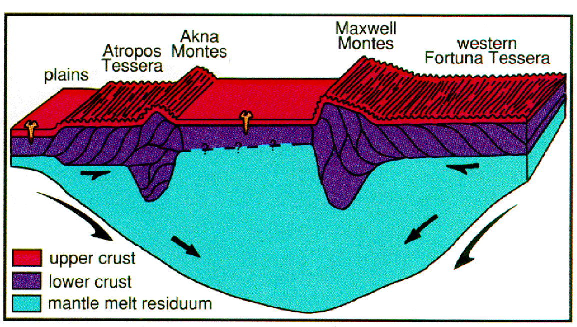

Figure 4: Cartoon of melt residuum concentration and tectonic deformation under western Ishtar Terra. [8]

Deep mantle consequences of ancient mobility. Whereas gravitationally inferred mantle anomalies may provide indications of residuum accumulation and/or surface mobility, a highly mobile surface should also result in a long-lived offset of the planet's center of figure from its center of mass. This is not observed to be the case on Venus, which has a modest 280-meter offset [9]. This places an important constraint on the extent of mobility that may have existed on ancient Venus (c.f. Fig. 5).

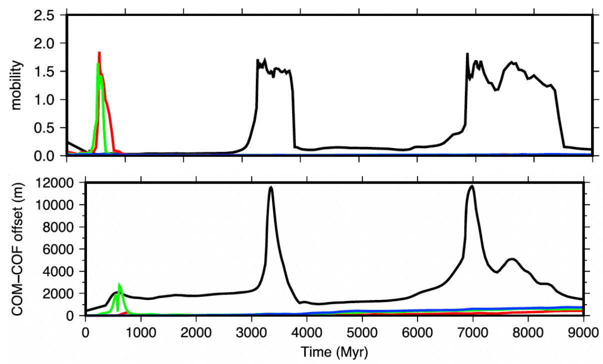

Figure 5: Evolution of mobility and the COM-COF offset for various initial conditions for planetary convection [10]

Future insights. The geographic concentration of depleted lithosphere on Venus could be explored further through joint interpretations of tectonic strain localization, crustal thickness, and mantle mass anomalies [11]. The long-wavelength portions of Venus's gravity and topography were sufficiently measured by Magellan; nevertheless, higher-resolution data from the upcoming VERITAS and EnVision missions will facilitate improved deconvolutions of shallow versus deep mass anomalies. Observations of thermal and compositional density anomalies in the lithosphere can also inform future modelling of mantle convection and tectonic regimes on ancient Venus.

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Could the Migration of Jupiter have Accelerated the Atmospheric Evolution of Venus?

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Abstract: In the study of planetary habitability and terrestrial atmospheric evolution, the divergence of surface conditions for Venus and Earth remains an area of active research. Among the intrinsic and external influences on the Venusian climate history are orbital changes due to giant planet migration that have both variable incident flux and tidal heating consequences. Here, we present the results of a study that explores the effect of Jupiter's location on the orbital parameters of Venus and subsequent potential water loss scenarios. Our dynamical simulations show that various scenarios of Jovian migration could have resulted in orbital eccentricities for Venus as high as 0.31. We quantify the implications of the increased eccentricity, including tidal energy, surface energy flux, and the variable insolation flux expected from the faint young Sun. The tidal circularization timescale calculations demonstrate that a relatively high tidal dissipation factor is required to reduce the eccentricity of Venus to the present value, which implies a high initial water inventory. We further estimate the consequences of high orbital eccentricity on water loss, and estimate that the water loss rate may have increased by at least ~5% compared with the circular orbit case as a result of orbital forcing. We argue that these eccentricity variations for the young Venus may have accelerated the atmospheric evolution of Venus toward the inevitable collapse of the atmosphere into a runaway greenhouse state. The presence of giant planets in exoplanetary systems may likewise increase the expected rate of Venus analogs in those systems.

Introduction: The current state of the Venusian atmosphere and the pathway through which it arrived there is an exceptionally complicated topic. Numerous studies have provided insights into the climate evolution of Venus and discussed primary influences on the atmospheric dynamics (Bullock & Grinspoon 1996; Taylor & Grinspoon 2009; Taylor et al. 2018). The evolutionary history of the atmosphere of Venus, and its potential divergence from a temperate "Earth-like" climate, depends heavily upon assumptions regarding the initial conditions. For example, Hamano et al. (2013) proposed that Venus may have never had surface liquid water oceans due to an extended magma surface phase. Alternatively, some models suggest that Venus may have had temperate surface conditions that allowed the persistence of surface liquid water until as recently as ~0.7 Ga (Way et al. 2016), depending upon assumptions regarding rotation rates and convection schemes (e.g., Leconte et al. 2013; Ramirez 2018). Such potential for past Venusian surface habitability has been the basis for defining the empirically derived inner edge of the "Habitable Zone" (Kasting et al. 1993; Kopparapu et al. 2014; Kane et al. 2016). The connection to planetary habitability has further fueled the relevance of Venus to refining models of exoplanets (Kane et al. 2019), both in terms of studying atmospheric chemistry (Schaefer & Fegley 2011; Ehrenreich et al. 2012) and detection prospects for potential Venus analogs (Kane et al. 2014; Ostberg & Kane 2019).

In the consideration of climate evolution, the orbital parameters of a planet can play a key role in the energy budget distribution over the surface of the planet (Kane & Torres 2017). In particular, it has been demonstrated that the orbital eccentricity can have significant consequences for the climate evolution of terrestrial planets (Way & Georgakarakos 2017; Palubski et al. 2020). Overall planetary system architectures can also play a role, such as the effect of Jupiter on impact rates (Horner & Jones 2008) and refractory elemental abundance (Desch et al. 2018) in the early inner solar system. Correia et al. (2012) showed that the eccentricity of planetary orbits can be increased by the excitation effects of outer planets that exceed the dampening effects of tidal heating. For those planets where the eccentricity contributes to significant tidal heating, the additional surface energy flux can trigger a runaway greenhouse for an otherwise temperate terrestrial planet (Barnes et al. 2013). Furthermore, the current rotation rate of Venus appears to be impacted by eccentricity and resulting solar tidal torques (Ingersoll & Dobrovolskis 1978; Green et al. 2019), in addition to interactions between the atmosphere and topography (Fukuhara et al. 2017; Navarro et al. 2018)

Results: Using the results of our extensive suite of dynamical simulations, we extracted the minimum and maximum orbital eccentricities attained by Venus for the full range of Jupiter semi-major axis values. Our eccentricity data show that the most powerful perturbations to the Venusian orbit occur when Jupiter is located in the vicinity of 4.3 AU. The maximum Venusian eccentricity of 0.31 occurs at a Jupiter semi-major axis of 4.31 AU. If Venus once had an orbital eccentricity as high as 0.31, then the question remains as to how the orbit circularized to its current state. One of the most efficient mechanisms to circularize a planetary orbit is through tidal interactions between the planet and its host star. Our tidal dissipation calculations suggest that the effects of tides may have played a key role in circularizing and stabilizing Venus's orbit. We found that the current value of Venus's tidal dissipation is not enough to achieve this, suggesting that Venus was not as dry in the past as it is today. To circularize its orbit over the timescale of the age of the solar system (~4000 Myr, post gas phase and migrations), the dissipation factor needed is 1.5 current Earth values. This suggests that Venus might have had a water-rich past, possibly in the form of surface or sub-surface oceans.

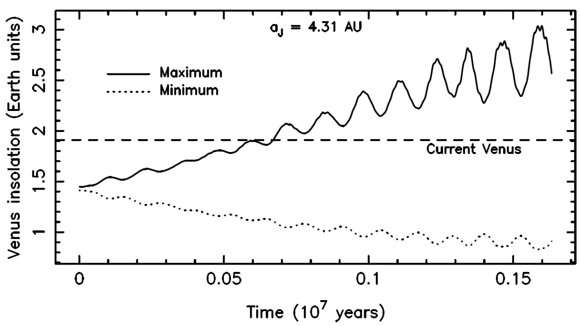

Figure 1: Maximum insolation (perihelion passage) and minimum insolation (aphelion passage) at Venus as a function of time.

To simulate the expected insolation flux of Venus during a possible early era with a high eccentricity, we adopt a solar luminosity that is 75% of the current value. At the semi-major axis of Venus, this results in an insolation flux of S/S0 = 1.43, where S0 is the present-day solar flux received at Earth. The evolution of the maximum flux (perihelion) and minimum flux (aphelion) received by Venus is represented in Figure 1. Venus starts in a circular orbit, then the rise in eccentricity results in a maximum insolation flux that rapidly starts to oscillate high above its present value, indicated by the horizontal dashed line.

Conclusions: The study presented here specifically investigates the effect of possible orbital dynamical scenarios on the evolution of an early Venus. Our simulations and subsequent analyses demonstrate that (1) the eccentricity of the Venusian orbit is dramatically increased for particular locations of Jupiter and (2) the consequences of the increased eccentricity would have included a significantly increased rate of surface liquid water loss. Our investigations of tidal dissipation and circularization timescales show that damping the eccentricity perturbations of Venus to their current value requires a larger initial water inventory than that for the current Earth, lending credence to the notion of substantial water delivery to an early Venus.

These results have been published in the Planetary Science Journal (Kane et al. 2020).

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Venus, Earth's Divergent Twin: Observations Constraining the Transition from a Mobile Lid Convection Planet to a Stagnant Lid Convection Planet

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Introduction: Mantle convection within Venus today is widely considered to exist in the stagnant lid regime, with a thick thermal lithosphere and limited surface motions [e.g., 1]. However, Venus in the past may have had a more Earth-like, mobile surface. The transition from mobile lid convection to stagnant lid convection may have been driven by global climate change. A convective transition from mobile lid to stagnant lid can be driven either by increasing the resisting force (fault friction) or decreasing the driving force (thermal buoyancy) for the convective flow [2]. Loss of water in the form of pore fluids increases friction on faults [3], increasing the resistance to mobile lid flow. Increasing the surface temperature reduces the temperature contrast across the upper thermal boundary layer, reducing the driving force for convection. Both processes likely act in superposition.

Recent studies suggest that climate change and changes in mantle convection style may be strongly coupled: the transition from mobile lid to stagnant lid convection results in strong, transient fluctuations in the rate of volcanic outgassing of the greenhouse gas CO_2 [4], while climate evolution models are facilitated by these spikes of enhanced volcanism [5]. In this abstract, we summarize evidence for a transition in convective style from a mobile lid in the past towards a stagnant lid at present on Venus.

A Mobile Lid Past

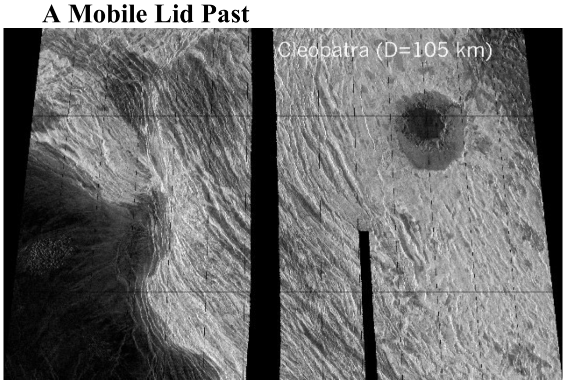

Figure 1: Folded mountain belts in Maxwell Montes. The image is 625 km across. The circular object at upper right is the crater Cleopatra.

The strongest evidence for mobile lid mantle convection at some point in the past history of Venus is the Ishtar Terra highland. Ishtar consists of Lakshmi Planum, a flat central plateau, surrounded on most sides by mountain belts. Lakshmi is typically about 3.5 km above mean planetary radius, while the mountain belts are 6-10 km in elevation [6]. Tectonic structures in the mountains (Figure 1) indicate an origin by compressional deformation, possibly as fold-and-thrust belts [7-9]. Gravity data suggests that much of Ishtar is supported isostatically [10] by crust that is roughly double the thickness in the surrounding plains [11].

The thickened crust and folded mountain belt morphology are best explained by crustal convergence driven by convective flow in the mantle, indicating that Venus preserves evidence for a past epoch of mobile lid convection recorded in its present-day surface and gravity. Structural relationships in Tellus Regio have been interpreted as forming due to lateral transport and assembly of several distinct tessera blocks [12], providing additional evidence for a mobile lid convection epoch.

A Convective Transition

Venus is dominated by lowland plains, which may record a transition between an early mobile lid epoch and the present-day stagnant lid epoch. Ridge belt networks occur in some low-lying plains on Venus, such as Lavinia Planitia and Vellamo Planitia [13, 14]. For example, Vedma Dorsa is ~1700 km long, with ridges that are typically 30-70 km wide but sometimes reach more than 200 km in width [6]. The Vedma Dorsa ridges are 0.5-1 km high and commonly asymmetric in cross-section. Ridge belts have been interpreted as due to thrust faulting and folding from crustal convergence over cold, downwelling mantle [13, 14], consistent with gravity data indicating dense mantle [15].

Ridge belts are prominent in radar imagery, but elastic fault dislocation models indicate that only 1-2 km of fault displacement is required in three representative study sites [14] in Vedma Dorsa. This indicates that the amount of horizontal deformation present in the plains is far less than in Ishtar Terra and the tessera, consistent with the possibility that the plains are from a transitional period in Venus history.

Ridge belts are distinct from wrinkle ridges [16, 17], which are ubiquitous on the Venus plains but typically less than 2 km wide and with limited topographic relief, suggesting very limited horizontal displacement. Stratigraphic relationships among the wrinkle ridges show that both the plains and the wrinkle ridges are not all the same age but instead formed over several hundred million years [18].

The Present-day Stagnant Lid

Both geophysical and geological evidence suggests that volcanic rises, rifts, and at least some coronae are young. Finite element simulations tested by long-wavelength geoid and topography observations show that Atla Regio and Beta Regio, the two largest volcanic rises, are dynamically supported by hot, rising mantle plumes [19]. Gravity and elastic flexure models also indicate that the Devana Chasma rift and large coronae such as Artemis, Diana and Dali Chasma, and Eastern and Central Eistla Regio are also dynamically supported by hot mantle [20-22].

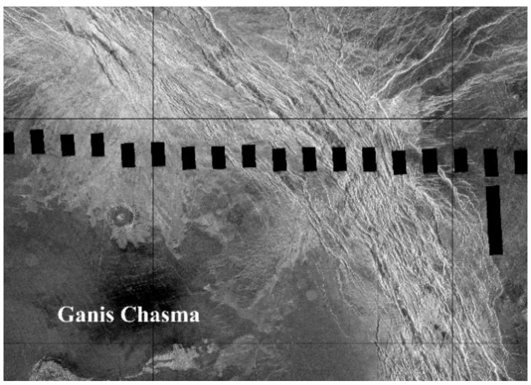

Figure 2: The Ganis Chasma rift is an analog to continental rifts on Earth. The image is 700 km across.

If not actively maintained by convective upwellings, these thermal anomalies will disappear within 100-200 million years by a combination of advection and thermal conduction. Thus, these structures all must be young in both a relative sense and an absolute sense. We refer to this as “gravitational stratigraphy”. Although geophysical anomalies are not a common stratigraphic tool, they can sometimes be useful given the paucity of useful geologic age indicators on Venus. The inferred young ages are consistent with the relatively low crater densities in these regions [23].

Extension at Balch Crater and structural mapping indicates typical extension of 4-8 km along Devana Chasma between Beta Regio and Phoebe Regio [24-27]. These values are typical of those found at continental rifts in the Rio Grande Rift and in East Africa [27]. The combination of geologic youth, as inferred from the geophysical observations, and limited horizontal extension is strong evidence that Venus mantle convection is currently transitioning into the stagnant lid regime; models indicate that this transition can take ~1 billion years [2], and Venus may not have completed the transition. Ganis Chasma in Atla Regio (Figure 2) has similar morphology and dimensions to Devana Chasma, suggesting that it too has limited total horizontal extension. The absence of clear hotspot tracks associated with the Atla and Beta plumes is another line of evidence favoring limited surface motions at present.

Gravity modeling of Artemis and Quetzalpetlatl suggests the presence of subduction at these two large coronae [28]. This does not disprove our hypothesis that Venus is transitioning from a mobile lid to a stagnant lid convection because modeling shows that such a transition is spatially and temporally complex, including for instance epochs in which one side of the planet temporarily has a mobile lid and the other side has a stagnant lid [2]. The overall evolutionary sense of the observations laid out here is from mobile lid convection towards a stagnant lid, consistent with a possible climate-driven loss of pore fluids, resulting in an increase of fault friction.

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WHEN AND HOW DID VENUS RESURFACING BEGIN? S. D. King and G. T. Euen, Department of Geosciences, Virginia Tech, Blacksburg, VA (sdk@vt.edu)

Introduction: The impact cratering record on Venus shows that Venus underwent a global resurfacing event between 200-700 Ma. followed by a dramatic reduction of volcanism and tectonism [1]. Two models have been proposed to explain the resurfacing history: equilibrium [2] and global [3] resurfacing and these endmember models continue to be debated. Observations that constrain surface tectonics prior to the resurfacing event remains elusive.

Convection modeling has shown that global overturns driven by lithospheric instabilities can repeat with intervals as frequent as 500-700 Myrs [4, 5]. Thus while we know that Venus underwent a global resurfacing event 200-700 Ma, we don't know much about the tectonic and volcanic history prior to resurfacing. (Some tesserae may represent fragments of an older terrain; however, the relationship between the tesserae and global resurfacing remains unclear.) We lack observations that constrain the surface of Venus prior to the global resurfacing event. If multiple episodes of global overturns occurred on Venus, the present surface tectonics and volcanism may only record the most recent event. In the absence of direct observational constraints, spherical shell convection calculations can guide our thinking about the possible early tectonic and volcanic history scenarios on Venus.

Stable Patterns of Convection in a Spherical Shell: Busse [6] showed that the low-Rayleigh number convective planforms (patterns) in a spherical shell are based on Platonic solids—the five geometric solids whose faces are all identical, regular polygons meeting at the same three-dimensional angles. Platonic solids consist of the tetrahedron (or pyramid), cube, octahedron, dodecahedron, and icosahedron. Busse [6] showed that tetrahedral, cubic, octahedral, and dodecahedral planforms are stable solutions in steady-state spherical shell convection as the Rayleigh number is progressively increased and hints at a steady solution for the icosahedral planform (Figure 1). Busse [6] further shows that all asymmetric patterns—that is all odd spherical harmonics—are unstable, even at low Rayleigh numbers.

Bifurcations and the pattern of convection. In the study of dynamical systems, a bifurcation occurs when a small smooth change made to a parameter causes a sudden 'qualitative' or topological change in its behavior. For example, the convective pattern in a sphere bifurcates from tetragonal to cubic to dodecahedral as the Rayleigh number is increased [6]. Thus each transition in pattern identified by Busse is a bifurcation. The importance of this is that these changes in pattern are a response of the system to a change in conditions and not the result of an external (exogenic) forcing.

While the steady-state convection solutions used in stability analysis [6] are not directly relevant to a large cooling planet such as Venus, King [7] showed that as a hot, stagnant-lid, internally-heated, spherical-shell cools the pattern of plumes and downwellings (planform) transitions from an initially icosahedral pattern (l=8,m=6) to a dodecahedral pattern (l=6,m=5) to a cubic pattern (l=4,m=4), then to a tetrahedral pattern (l=3,m=2) and finally a symmetric two-plume pattern (l=2,m=0). The progression of patterns is identical to the bifurcations that would be observed with decreasing Rayleigh number [6]. In internally-heated, cooling calculations, the effective Rayleigh number will be decreasing as the internal temperature and concentration of radionuclides decreases. King [7] also confirmed that long-wavelength asymmetric conditions (perturbations represented by odd spherical harmonics) are unstable, usually leading to global overturns driven by lithospheric instabilities. While hard to visualize among the short-wavelength lithospheric drips and plumelets, the icosahedral pattern is clearly visible in the geoid and dynamic topography.

Application to Venus: As a result of fast accretion, the interior of Venus started hot with a short wavelength (high spherical harmonic degree pattern). Radiogenic decay may have heated the interior further for the first billion years however this heating peaks within the first billion years and the initial short wavelength pattern of convection settles down into an icosahedral pattern (l=8,m=6) that can remain stable for 1-2 billion years. Even though the interior is dominated by small-scale lithospheric drips and plumelets, an in the icosahedral pattern (l=8,m=6) of plumes from the core to the lithosphere remain stable for an unexpectedly long period of time. These surprisingly stationary plumes may be responsible for clusters of coronae, in much the same way that deep superplumes in Earth's lower mantle are envisioned to anchor smaller upper mantle scale plumelets [8]. This highly symmetric icosahedral pattern of convection prevents the lithospheric instability required to initiate a global overturn event.

Asymmetric initial thermal anomalies with wavelengths shorter than spherical harmonic degree 8 evolve into the icosahedral pattern with stable plumes—making the icosahedral pattern a bottleneck in the development of the long-wavelength asymmetry from short wavelength initial conditions.

I lift up my eyes unto the sky, from whence cometh my help. Because the lithospheric instability necessary to initiate a global overturn does not develop naturally during the cooling of an internally-heated spherical shell, we suggest that a giant impact—which would deposit heat preferentially within one hemisphere—could provide the necessary asymmetric thermal condition to initiate a global overturn. As a giant impact would likely have occurred early in solar system history, this suggests that the overturn responsible for the present surface of Venus was the latest in a series of overturn events. King [7] casts doubt on the global overturn mechanism noting that the small offset between the center of mass and center of figure of Venus is difficult to reconcile with global overturn events because the asymmetric deposition of cold lithosphere deep into the interior increases the center of mass and center of figure offset.

Conclusion: Regardless of whether the equilibrium or global resurfacing model is responsible for Venus present day surface distribution, the interior of Venus likely began as a vigorously convecting spherical shell with a short wavelength pattern of drips and plumelets. In the absence of a large (giant?) impact, the interior would have passed through a stable icosahedral convective phase and as it continued to cool evolved toward longer-wavelength patterns following patterns of Platonic solids (Figure 1). In the absence of an endogenic mechanism to force the system into an asymmetric pattern—necessary to initiate a global overturn mode—the tectonics and volcanism would be regulated by equilibrium resurfacing with present day internal mantle structure dominated by one of the patterns observed in Figure 1. The small offset between the center of mass and center of figure favors the equilibrium resurfacing model however the low retrograde rotation may be consistent with a giant impact, which would trigger the global resurfacing mechanism due to the asymmetric deposition of heat from the impact. However, mechanisms including silicate melting and water loss may introduce additional asymmetries [5].

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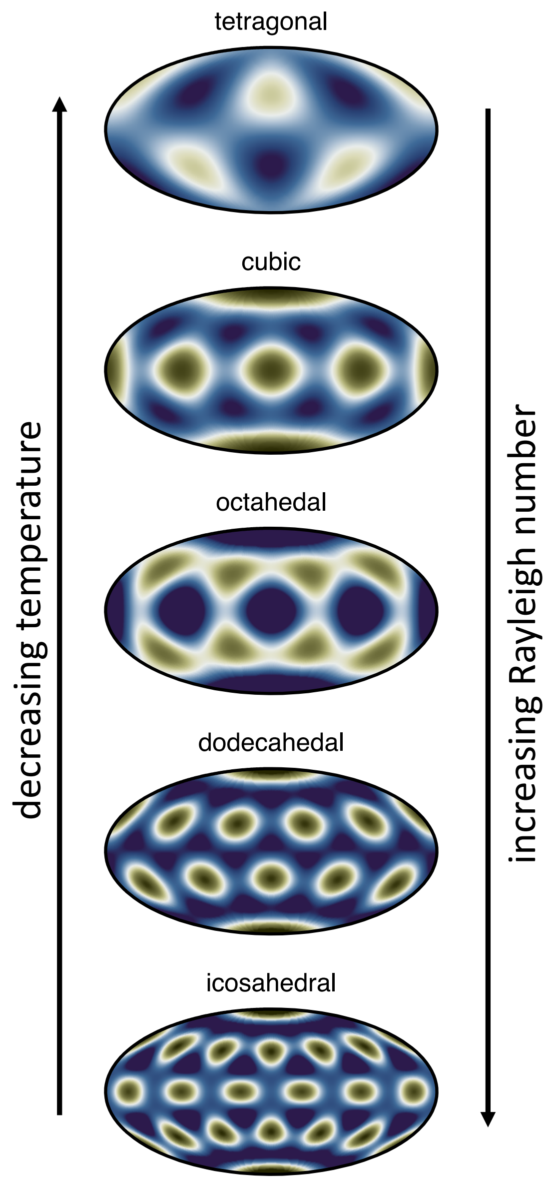

Figure 1: Planforms of convection in a spherical shell, gold representing upwelling plumes while blue represents downwellings. The patterns follow the forms of Platonic solids. Each pattern represents a bifurcation as the Rayleigh number increases. However the patterns also evolve in internally heated spherical shells as the shell cools.

Adv., Max Endurance, VTOL & Sample Return Capable, Mission Agnostic Planetary 4D Explorer [4DPE]

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Intro: ✈NEW RONTIER TECHNOLOGY GROUP✈ proposes a highly efficient, maximally versatile, large payload capable, optimally powered ultra-light glider-rover to explore the entire surface and atmosphere of most bodies for continuous, extended missions having an **unprecedented** duration of up to 30 years. Several landing and take-off VTOL embodiments are possible. Low cost networked constellations, including surface vehicles and probes of our design, can be repeatedly deployed in a single mission or over many years for absolute 4D coverage. Low cost sample return missions are enabled in short time for most bodies. NOTE: this paper mostly discusses Venus as it is at the top of NASA's list of mission priorities with a significant atmosphere and is most challenging of all bodies.

Viability: At its core, the glider architecture is similar to ones implemented in several terrestrial platforms, including NASA's Pathfinder/Helios [1], Sunglider [2] and the ApusDuo [3] which fall into a new category of craft called High Altitude Pseudo Satellites (HAPS). As such, the platform is a proven solution although the 4DPE has significantly greater endurance, performance & versatility.

Relevance and Alignment: NASA, ESA and others are developing concepts for controlled variable-altitude balloons in order to study Venusian atmosphere at altitudes ranging from 52-62 km. Not only is the 4DPE able to operate at higher altitudes bu also capable of descending below the 30 km cloud deck to directly explore points of interest up close.

In addition to carrying a large suite of scientific equipment, the high capacity 'mother ship' is capable of deploying various long endurance attritional mission specific micro-vehicle networks, such as free balloons, gliders, tethered probes, and/or surface and/or subterranean probes/vehicles to extend the effective operating range and scientific research capability of the 4DPE in 4D space as required by a range of missions.

Several vertical landing and take-off [VTOL], roving capable, embodiments that will explore ANY areas of interest in detail are considered. Imaging and research is then possible at any altitude, on surface and even below surface using recoverable, reusable probes and vehicles. **Several sample return architectures have been explored which provide a unified collection of samples covering vast, diverse locations in 4D.** This level of audacious technology and exploration is not possible using balloons or any other platform under consideration by others.

Besides being costly and short lived, the balloons and airships being proposed by others have poor motivity control which then provides limited value for scientific endeavors and can potentially strand the craft in the detrimental elements. Moreover, since the Sun rises and sets every 117 Earth days on Venus, there is a distinct possibility that a balloon would be stranded on the night side of Venus for long periods of time and may possibly never recover operationally. 4DPE's dynamic motivity control prevents such fate.

Basic Operation of Core Embodiment: [Note: re-entry dynamics have not been closely examined yet] To lower the mission costs, the 4DPE will deploy in space, slowing down in the upper atmosphere by shedding the transit velocity from Earth in a dynamically controlled low angle descent, possibly assisted by an external aero breaking device. This long flight path will allow highly maneuverable circumnavigation and exploration at high altitude over an extended period without energy input. Following the slow down phase, the propulsion system or maneuvers will sustain flight for as long as the craft materials allow which will be impacted by the mission profiles but will be on the order of decades. **Note**: mission energy supply is not a concern or a temporal limiting factor.

Moreover, operating virtually as a gliding parachute from time of deployment, the craft can be made significantly larger or lighter than ones that take-off from and land on the ground on Earth, further improving its performance in critical metrics.

Such a design is highly scalable in size and load capacity as missions require, making the architecture highly versatile.

Several techniques for landing on, exploring and returning samples from airless bodies are possible using our concepts.

Technical Concept / Design: Current HAPS utilize very efficient wing profiles in order to operate between 50,000 and 80,000 feet. At first, these may be too bulky and thus unsuitable for transport. In inaugural missions, the 4DPE wing design may take the form of highly stowable fabric/foil wings similar to those found in paragliders or hang gliders. Other architectures are enabled by our propulsion and designs. An optimal wing and craft design will likely have to be developed for each mission type.

The core 4DPE embodiment combines two sets of light wings: a set of rotary wings called "proprotors", mounted in our unique thrust vectoring architecture for maximal power, maneuverability and simplicity, and two pairs of fixed, high aspect ratio wings for large glide ratio with minimal drag [CL/CD >>70] and low stall speeds which allows detailed planetary science. The design minimizes interference with the proprotor thrust for maximally efficient flight at any regime including VTOL operations.

Several aircraft iteration allow Vertical Taking Off and Landing (VTOL) and Short Take-off and Landing (STOL) capabilities. Such landings would be brief to prevent damage from the Venusian environment but are maximized by active cooling. Another iteration would incorporate a hybrid aerodynamic airship/balloon that produces dynamic and static lift to carry most or all of the system weight. This design could lift-off from the surface with little or no input in energy yet have full control authority over the entire flight envelope. Designs under consideration by others are unable to execute all of these capabilities and missions.

Venus orbits the Sun at an average distance of about 0.72 AU (108 million km; 67 million mi), and completes an orbit every 224.7 days while the planet rotates clockwise on its axis in retrograde rotation [solar / universal reference coordinates] once every 243 Earth days—the slowest rotation of any planet. Because of the retrograde rotation, the length of a solar day on Venus is significantly shorter than the sidereal day, at 116.75 Earth days. Venusian equator rotates at 6.52 km/h (4.05 mph). [Earth's rotates at 1,674.4 km/h (1,040.4 mph)]. Speed of the 4DPE is significantly higher, allowing constant exploration in stationary loitering mode during constant maximal daylight or darkness, as required.

However, the hot, acidic atmosphere of Venus moves westward (prograde) in some places up to 60 times faster [~240 mph] than its retrograde surface, whirling around the planet once every 96 hours, an effect known as super-rotation, creating wind shear conditions that enables an energy input-free and even propulsion-less proven method, called dynamic soaring, to extract propulsive and system energy from atmospheric wind to power the mission potentially indefinitely, if it allows for this highly characteristic motivity. As such, heavy propulsion system batteries might not be necessary, adding to mission flexibility at significantly lower costs.

Compared to current HAPS architectures, the advanced, efficient, light weight propulsion system allows much smaller and lighter vehicle, for higher altitude and greater area of operation or increased payload capacity.

FACTOR	LAND	AIR	4DPE
Maturity	Low	Low	Good
Wear / dust	Severe	Low	Low
Navigation	Complex	Simple	Simple
Range	Low	Good	Unlimited
Speed	Low	Moderate	High
Payload	Low	Moderate	High
Thermal	Challenging	Simple	Simple
Delivery	Small lander	No lander	No lander
Operating Envelope	Low	Good	Unlimited
Utility	Low	Low	High
Data Size	Low	Low	High
Data Value	Low	Low	High
Mission Cost	Moderate	Moderate	Low
Mission Value	Low	Low	High
Mission Sophistication	Low	Low	High
Mission Duration	Low	Low	High
Science Advancement	Low	Low	High
Technology Advancement	Low	Low	High

Hurdles: We are not aware of any significant parameters that may constraint the primary or ancillary architectures.

Conclusion: The system designs, modularity, scalability, versatility and economics clearly demonstrate superior solutions which will enable sustained exploration presence on Venus, Mars and beyond for years to come. Terrestrial applications abound.

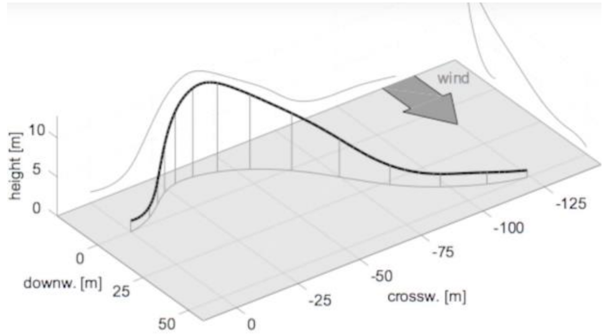

Fig.1 energy-free dynamic soaring using wind energy

Opportunities: ℕ𝔽𝕋𝔾 and its associates are open to collaboration with qualified strategic partners for all concepts discussed here and a broad suite of innovations discussed elsewhere[4, 5, 6]

Other - science: In regards to the planetary temperature - we believe the heat of Venus is caused by an electrodynamic phenomenon akin to a homopolar motor/dynamo that is working against the solar system electric circuit where the sun is the primary driving element [magnet, stator of a motor] and source of current and conduction medium [electrons, ions, plasma] and Venus is the driven electrodynamically coupled out of phase element [rotor of a motor]. Lacking a tidal locked moon, Venus flipped 180° on its axis and is now generating heat due to imbalance in the circuit. This is evidenced by the high prograde wind and slow retrograde rotation which is an artifact of the previous prograde rotation. Depending on the state of this process, the slow rotation is either evidence of deceleration or acceleration. Although historical human records indicate that Venus experienced a recent cataclysmic event accompanied by magnificent light show and devastation on Earth, this might have an origin in a massive meteor impact that destroyed the planet dynamo/magnetic field and added to the heat the planet is exhibiting.

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MULTIPLE TECTONIC AND VOLCANIC EVENTS: GINA CRATER AREA, VENUS.

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Introduction: A current controversy in the geology of Venus centers on the age(s) of its highlands – the tesserae. One view of Venus' past is that it experienced a global resurfacing event at ~1.5 Ga, now represented mostly by volcanic plains, and that the tesserae represent earlier crust deformed in that event [1,2]. It is also argued that the resurfacing represents multiple volcanic events over long times [3,4]. The ancient age of tesserae has recently come into question [5,6]. Some tesserae include distinct morphologic units that could represent deformed plains material [5,6]; in other cases it is possible that tesserae are forming today [7]. To address this question, we are mapping a tessera-plains transition around Gina Crater, near Venus' north pole.

Gina is a ~15 km diameter crater at 78.1°N, 76.3°E (Fig. 1), in the Snegurochka (V1) quadrangle [8]. Gina is on the western boundary of the Szél-anya Lineae belt (mapped mostly as tessera [8]), where it abuts a broad area of regional volcanic plains [9]. The area is complex, with evidence for multiple episodes of tectonism and volcanism and was specifically chosen to help constrain the timing of deformation events relative to those of volcanic emplacement.

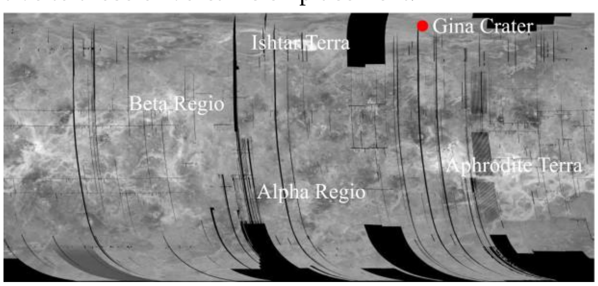

Figure 1. Location of Gina Crater at 78.1°N, 76.3°E.

Data & Methods: We used the Magellan SAR left-look global mosaic (nominally ~75 m/pix resolution) as the basemap. The area was not imaged in Magellan SAR right-look or stereo-look campaigns. The image was acquired from USGS Map-A-Planet 2 [10]. We used ArcMap 10.6 to compile our observations and the JMARS web interface for general visualizations.

Morphologies: Morphologies are defined by shape, orientation, and SAR backscatter. Tectonic features are classified as fractures/ridges, grabens, faults, and lineaments. Fractures/ridges are distinguished by their superposition & cross-cutting relationships, lengths, and connectedness. Grabens are mapped as paired SAR-dark and SAR-bright slopes. Faults are mapped where surface features are offset. Lineaments are mapped as bright, straight lines.

Map Units: Map units are identified based on differences in radar brightness, morphology, texture, and stratigraphic relations, according to USGS guidelines [11]. Units are generally defined based on observations of emplaced material, but when material is obscured by deformation, the unit is characterized by deformation. The geologic history of the area is constructed by examination of stratigraphic relationships among units, with an emphasis placed on superposition, crosscutting, and embayment relationships. Contacts are defined by embayment relationships, radar brightness, and deformation morphology and volume.

Results: The descriptions of mapped units (Fig. 2A) are in approximate chronological order.

Fold Belt: Northwest of Gina Crater and the regional plains is a belt of SAR-bright discontinuous parallel ridges, trending NE-SW (*pdl*). The ridges average 1.5 km wide and are separated by 0.5-4 km. The belt is embayed by regional plains units (Fig. 2C) and is cut by fractures/faults of several orientations.

Regional Plains: South of the fold belt and west of Szél-anya Lineae is an area of low-backscatter plains. We distinguish eight units. Six units have low radar backscatter and are differentiated by deformation characteristics. The *pdf* unit is densely fractured or cracked in a pattern of connected polygons and is cut by wrinkle ridges. The *pdd* unit has fewer polygonal fractures, which are less obviously connected; it shows wrinkle ridges, but they are smaller and more localized than in *pdf*. The *pds* unit grades by increasing backscatter into other plains units. *Pds* shows few fractures and few short wrinkle ridges, both of which tend to be isolated from each other. The *pbn* runs adjacent to the main fracture belt. *Pbn* contains very fine-scale fractures and large wrinkle ridges that superpose *pdf* and *pdd*. The *pdb* and *pdub* units have a very low SAR backscatter and are surrounded by *pdf*, *pdd*, *pds*, and *pbn*. *Pdb* is recognized as sharply bounded patches and shows no evidence of deformation (perhaps from its low SAR backscatter), whereas *pdub* patches are diffuse. Two plains units have greater radar backscatter. The *pbs* unit is relatively smooth and is deformed by long, sinuous wrinkle ridges and lineaments, whereas *pbd* has shorter wrinkle ridges and is commonly embayed.

Gina Crater: The Gina impact crater is at the border between Szél-anya Lineae and regional plains to the west. It is recognized by its rim (*cw*), ejecta (*cre*), and floor materials (*cfh*, *cfg*) (Fig. 2B). The crater is shorter E-W than N-S, perpendicular to the dominant fabric of Szél-anya Lineae. Hills and wrinkles on the crater floor are parallel to that tectonic fabric. On the crater floor is a small patch of low SAR-backscatter material (*cfd*, like *pdb*). Ejecta from Gina impinges on regional plains units (above) to its west; ejecta lobes to the east (onto Szél-anya Lineae) are indistinct.

Fracture Belt / Tessera: Szél-anya Lineae is a belt of heavily deformed rock on the east of the mapped area. Its structure is primarily N-S, marked by rock layering, fractures, and faults. These are crosscut by structures oriented ENE-WSW & SW-NE, and then by others oriented NW-SE. With such multiple deformations, the area is technically tessera [8].

Shield Volcanos: Shield volcanos occur on all units (except Gina). They are recognized as domes or mounds <10 km across and are of intermediate SAR backscatter. Many have depressions at their summits, and some show lobate extensions like lava flows. In most cases, fractures and faults do not extend into/across shield volcanos from the surrounding terrain. However, some shields (& their flows) are cut by faults/fractures and obscure others (Fig. 2D).

Interpretations: The Gina area is complex, with many episodes of eruption and deformation. The fold belt (*pdl*) is the oldest feature, pre-dating all the plains units. The plains are inferred to be basaltic but without detectable vents. The plains units have been deformed in multiple events. The tessera record at least three distinct deformation fabrics: NE-SW fractures, NW-SE fractures, and N-S deformation consistent with thrust faults (matching the orientation of Szél-anya Lineae). Gina Crater is on the boundary of the Szél-anya Lineae and plains units. Its ejecta lies on the plains units, so it post-dates their emplacement. Gina pre-dates some of the E-W compression of the Lineae.

The history of the plains and tessera are difficult to link but have their interaction with Gina in common. While Gina post-dates emplacement of plains units, it appears to have impacted into tessera material and is deformed, as was the tessera. This suggests that the tessera formed in multiple episodes of deformation while ongoing volcanism emplaced neighboring units. While the specific interpretation and geologic sequence of events seems reasonable for the Gina Crater area, it may not be applicable to all tesserae.

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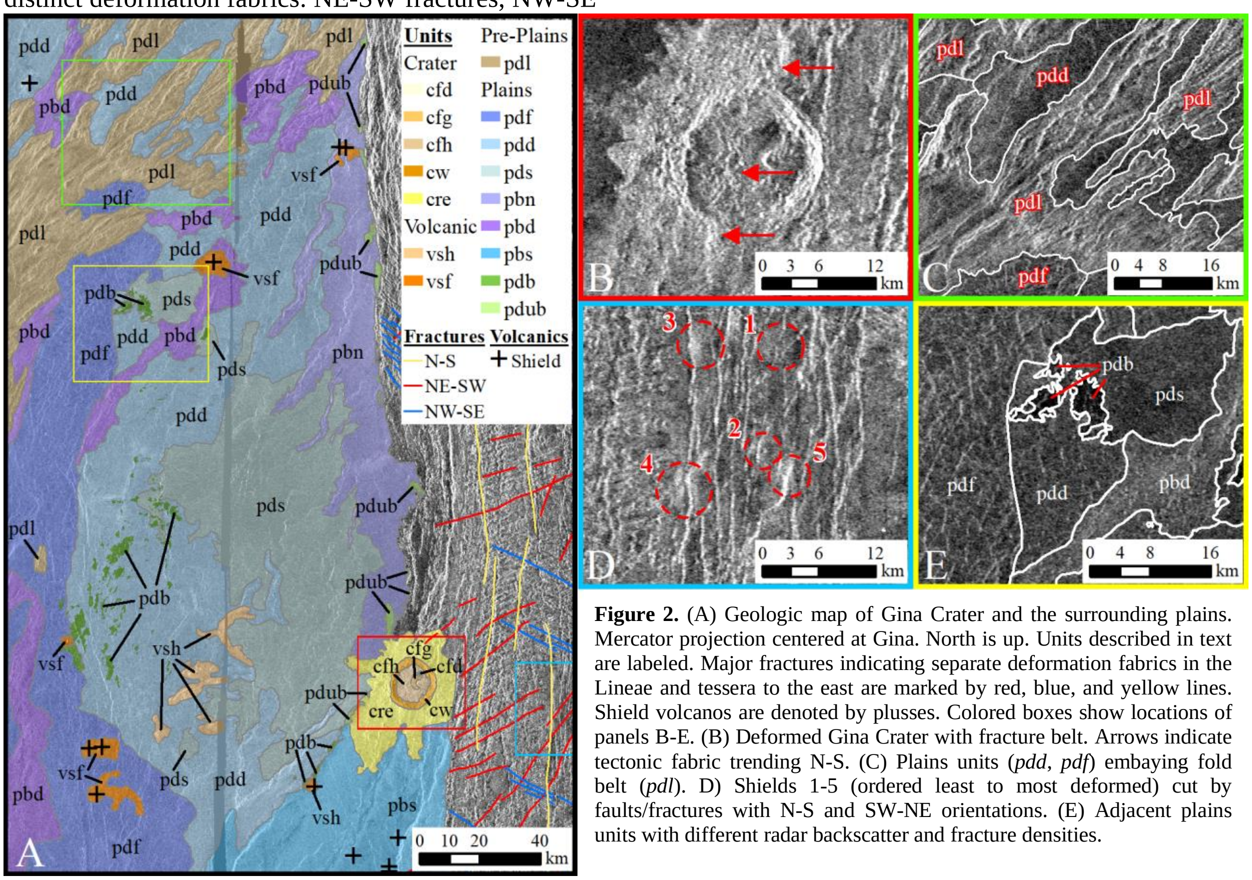

Figure 2. (A) Geologic map of Gina Crater and the surrounding plains. Mercator projection centered at Gina. North is up. Units described in text are labeled. Major fractures indicating separate deformation fabrics in the Lineae and tessera to the east are marked by red, blue, and yellow lines. Shield volcanos are denoted by plusses. Colored boxes show locations of panels B-E. (B) Deformed Gina Crater with fracture belt. Arrows indicate tectonic fabric trending N-S. (C) Plains units (*pdd*, *pdf*) embaying fold belt (*pdl*). D) Shields 1-5 (ordered least to most deformed) cut by faults/fractures with N-S and SW-NE orientations. (E) Adjacent plains units with different radar backscatter and fracture densities.

ATMOSPHERIC EFFECTS ON CRATER SIZE: PRELIMINARY RESULTS FROM A PILOT STUDY.

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Introduction: Venus, Earth, Mars, and Titan are the solar system planets where an atmosphere should be considered when interpreting the impact cratering and ejecta records. Of critical importance is an understanding of how an atmosphere might alter the diameter of a crater, and possibly influence interpreted ages of surfaces. Early explosion crater studies (Chabai, 1965, 1977; Johnson et al., 1969) attribute the reduction in size of small laboratory craters to atmospheric overburden pressures. However, because overburden pressure is less important for large planetary-scale craters, several investigations (Herr, 1971; Holsapple, 1980) conclude that atmospheric-related reductions are unlikely to be important.

Experimental, observational and theoretical evidence (Schultz, 1992a,b; 1993; Barnouin-Jha et al. 1999a,b and c) suggest this initial conclusion based on overburden pressure alone may be incorrect. Craters generate their own winds, as the ejecta push against the surrounding atmosphere. The resulting strong dynamic pressures appear to limit ejecta excavation and thus reduce the size of craters, especially at large scales where ejecta speeds increase with $\sqrt{R}$, where R is crater radius. In this pilot study, we use new measurement techniques, including high speed video, a laser sheet (Barnouin-Jha et al., 2007), and a sophisticated hand-held Artec Eva 3D scanner to address the science question, "How is impact crater morphology and morphometry affected by atmospheric pressure?" The need for such experimental studies of atmospherically-influenced cratering is all the more urgent given the trifecta of spacecraft heading to Venus at the end of the 2020s and early 2030s. As future spacecraft return higher resolution radar images and digital elevation models of Venus, we may find that variation in crater depth to diameter (D/d) ratios and/or morphologies are a proxy indicator for past changes in Venusian atmospheric density (e.g., Way and Del Genio, 2020), or reflect heteroegenities across the Venusian surface, though we acknowledge these signals could be convolved.

Methods: To begin to address our science question, we began a series of impact experiments in the Planetary Impact Lab (PIL) at the Johns Hopkins Applied Physics Laboratory (APL; Daly et al. 2021). We undertook subsonic impacts into a low density, fine pumice. We chose fine pumice that would be easily entrained by the impact-generated pressures produced in Earth's 1 bar of atmospheric pressure. We consider fine pumice and 1 bar of atmospheric pressure to be roughly analogous to much larger clasts in Venus' ~90 bar atmospheric pressure from the perspective of a force-balance of grain weight to atmospheric drag.

In our pilot study, we examined the morphometry of a crater formed in 1 atmosphere (760 torr) to the morphometry of a crater formed in near-vacuum (3 torr) under otherwise identical conditions. Our target material was Grade F pumice with a mean diameter of 75 µm ± 27 µm (1 σ), as measured with a Camsizer. Its bulk density is 926 kg m^{-3}. This very fine, low density target material is easily entrained in low speed winds in Earth's atmosphere, much more so than the several 100 µm diameter sand more commonly used in impact cratering experiments.

The nitrogen-pressurized cratering gun accelerated 6 mm alumina spheres massing 0.5 g to 250 ± 5 m/s with an impact angle of 90˚ to the horizontal (straight down). We made 3D morphometric scans of the crater with the Artec Eva Scanner.

Results: The atmospheric crater has a depth of 2.0337 cm and a diameter of 4.9874 cm, giving a very steep D/d of 0.41. The vacuum crater has a depth of 1.7517 cm and a diameter of 12.29 cm, giving a more crater-typical D/d of 0.14 (Figures 1, 2, 3). The rim and ejecta for the vacuum case are much more impressive than for the crater formed in an atmosphere. Our video assessments of crater growth show that in vacuum, later crater growth is much more extensive than for the atmospheric crater, resulting in more collapse during modification after excavation ceases.

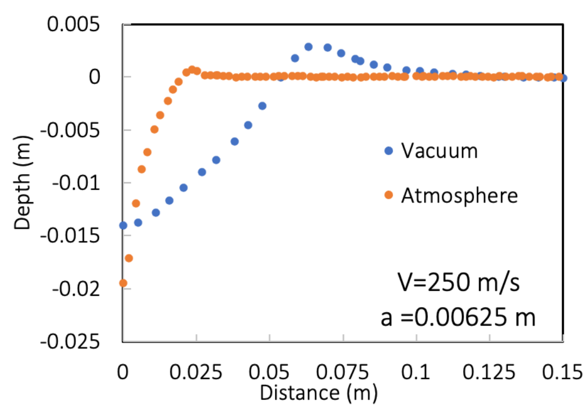

Figure 1. Radial profile of craters formed in vacuum and atmosphere. The atmospheric crater has much steeper sides than the vacuum crater.

Discussion, Conclusion and Future Work: Our work shows one experimental instance of profound atmospheric effects on impact crater formation and resulting morphometry in fine pumice and are at least qualitatively consistent with previous work (e.g., Schultz, 1993). Evidence for steep narrow walls and less extensive ejecta seen on Venus relative to the Moon, when comparing craters of similar size after accounting for the gravity differences, are consistent with what we find in this study. Assuming that

- fine pumice at 1 bar is an analog for much larger blocks in Venus' 90 bar atmosphere;
- that our experiments capture the atmospheric effects on crater formation; and
- that early time shock effects only affect small portions of a large Venusian crater (e.g., Sugita and Schultz, 2003),

we might expect that craters formed in Venus' lower density paleo-atmospheres would have shallower aspect ratios than craters formed in more modern Venusian atmospheric densities, though disentangling this affect from other factors could prove challenging. Relatedly, ejecta properties (e.g., runout, topography, and presence/absence of terminal ramparts) may vary as a function of atmospheric pressure. Future work will generate more statistically significant atmospheric cratering results with a wider parameter space for variables with especially important application for interpreting future spacecraft observations from Venus.

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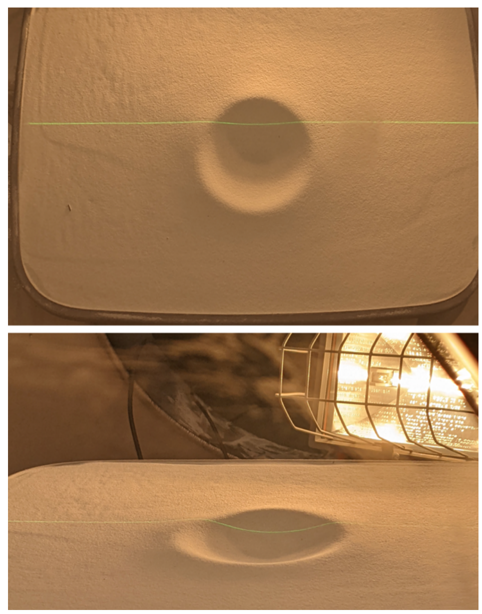

Figure 2. The 12.29 cm diameter crater made in near-vacuum (3 torr). A green laser sheet aids in morphometric analysis.

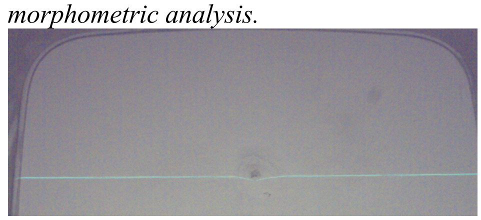

Figure 3. The 4.9874 cm diameter crater made at 1-bar of atmospheric pressure. The atmospheric crater is steeper, with a narrower rim and a deeper depth.

VENUS SCIENCE AND EXPLORATION AND PUBLIC ENGAGEMENT: A PROPOSAL. A. J. Shaner[1], S. R. Buxner[2], J. Balcerski[3], N. R. Izenberg[4], W. S. Kiefer[1], and A. H. Treiman[1], [1]Lunar and Planetary Institute, USRA (shaner@lpi.usra.edu), [2]Planetary Science Institute, [3]Ohio Aerospace Institute, [4]Applied Physics Lab, The Johns Hopkins University.

Introduction: The coming years of preparation for the long-awaited return to Venus presents a unique opportunity for the Venus science community to create and implement an organic, community-driven public engagement initiative – a collaboration between the global community of Venus researchers, the Venus Exploration Analysis Group (VEXAG), and public engagement professionals – to raise awareness in the American public of the current state of scientific knowledge of Venus and to generate interest in the upcoming missions (Fig. 1).

Fig. 1 *LPI scientists Dr. Gabe Eggers and Dr. Walter Kiefer answer questions during a public engagement event featuring Venus-themed music performed by Houston-based woodwinds quintet WindSync.*

This paper proposes the creation of a centralized Venus public engagement effort, led by the Lunar and Planetary Institute (LPI). The purpose of this effort is to provide public engagement guidance for the Venus community and act as a hub for collecting and sharing information about the Venus community's public engagement efforts.

Proposed tasks: The following are proposed tasks for this effort. These tasks will be coordinated by the LPI with input from the Venus community through VEXAG and individual mission teams. A first attempt to gather community input took place during the 2022 Lunar and Planetary Science Conference [1]. The feedback provided was a good start. Input from the community will continue to be solicited as tasks are finalized.

Common goals and evaluation. Creating common goals and objectives is an important and necessary early step for any collaborative effort. With common goals and objectives, common evaluation instruments (e.g., surveys) can be created for use by the community in various public engagement settings.

U.S. public knowledge survey. A survey will be created for distribution across the United States for adults 18 and over. The purpose of the survey is to obtain a snapshot of the public's current knowledge of Venus. This information may be useful for anyone conducting, or planning to conduct, Venus-themed activities and/or events with public audiences.

"Look up at Venus" events. Modeled after (possibly collaborating with) NASA's annual International Observe the Moon Night [2], an annual Venus observation event is a great way to engage audiences by simply looking up at Venus. Conversations can include why Venus is the third-brightest object in the sky and phases of Venus. Conversations around Venus as an astronomical object can then segue into conversations about how exploration of this diverse, geologic world will also teach us about Earth.

Web portal. An online presence will be created within the LPI's education and public engagement webpages. This webpage will feature resources for engaging public audiences (Fig. 2), opportunities for public engagement and other information the Venus community may find helpful.

Fig. 2 *An educational demonstration using "elephant toothpaste" to model the morphology of a Venusian pancake dome.*

Additional Information: The VEXAG Outreach SAW meets the third Thursday of each month. If you would like to participate in these meetings, please contact Andy Shaner – shaner@lpi.usra.edu – for meeting connection information.

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CHEMISTRY OF VENUS' RECENT BASALTS AS CLUES TO ITS ANCIENT PAST. A. H. Treiman[1] and J. Filiberto[2], [1]Lunar and Planetary Institute, 3600 Bay Area Blvd. Houston TX 77058 <treiman@lpi.usra.edu>, [2]ARES/XI, NASA Johnson Space Center, Houston TX.

Introduction: Perhaps the most important question about Venus is whether it ever had a hydrosphere: liquid water, oceans, and thus an environment suitable for life as we know it [1]. The D/H of Venus' atmosphere suggests extensive water loss [2], and climate models may be consistent with global oceans [3,4]. Rocks dating from that epoch may be preserved in Venus' tesserae (and especially Ishtar Terra) – inferred to of felsic or silicic rock [5], which would suggest abundant water [6]. However, the exact elemental compositions of tesserae (silicic or not) will be difficult to retrieve and most of Venus' surface is basalt flows and volcanic constructs, inferred to be much younger than the oceanic epoch. Remotely sensed data are (and will be) ambiguous about the specific rock types that make up tesserae [7,8], and lander spacecraft are almost certain (in the near term) to avoid the rough and precipitous topography of the tesserae and touch down instead on flat, safe basaltic plains [9] or volcanic rises [10].

'Recent' basalts at Venus' surface could preserve chemical tracers of an ancient aqueous past, if their source regions (material that was re-melted) had been affected by water. This scenario occurs on Earth in Island Arc Basalts (IAB), where their compositions are thought to reflect aqueous alteration of parental mid-ocean ridge basalts (MORB) and incorporation of oceanic sediments [11]. Ancient Venus might have supported plate tectonic [12] and thus have had IAB equivalents; absent plate tectonics, basalt affected by aqueous alteration could have been cycled into its mantle by burial under thick sections of later basalt [13].

Our purpose is to suggest specific chemical clues in current basalts that would permit recognition of those with a history of aqueous interactions from those that did not. We compare Earth's Ocean Island Basalts (OIB) that involved little water with IAB that show chemical effects ascribable to water. It is not clear that Venus' basalts can be mapped into terrestrial tectonic settings [14]; however, it seems reasonable that aqueous geochemical processes could have (had) similar effects on both planets.

Data and Methods: The chemical compositions of Venus basalts are known from X-ray fluorescence (XRF) and gamma-ray spectroscopy (GRS) analyses by the Venera and VEGA lander spacecraft [5,15]. These data are of uncertain and poor (by modern standards) quality because of the instrumentation available at the time and the limited information available on standards and data processing. None-the-less, these analyses are all we have, and are accepted provisionally as accurate.

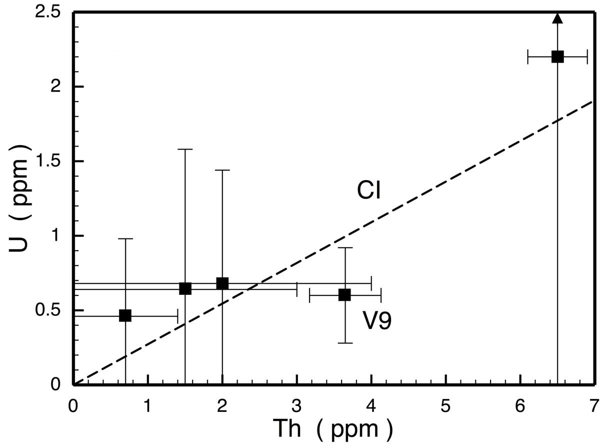

Figure 1. U vs. Th for Venus basalts [15], uncertainty bars are reported 2σ. The Venera 9 rock (V9) [16] has a sub-chondritic U/Th ratio; other analyses are consistent with a chondritic U/Th ratio.

Chemical compositions of Earth basalts, OIB and IAB, are from the extensive literature.

Indicators of Aqueous Action: Geochemical indicators of ancient aqueous activity could be preserved in 'recent' basalts, provided that the conditions during melting and emplacement did not significantly alter abundance ratios of specific elements. Most of these 'unalterable' elements are incompatible in normal igneous processes – i.e., they do not partition significantly into basaltic igneous minerals (olivine, pyroxenes, feldspars) vs. basaltic magma.

Uranium-Thorium. Uranium and Th are refractory, lithophile, and incompatible in igneous processes; the U/Th ratio should be unaffected by most processes of planet formation and differentiation, and remain at the chondritic (CI) value (Figure 1). However, U is readily mobilized in aqueous fluids (as UO_2^{-2}), while Th is not [17]; this could help explain why Earth IAB typically have non-CI U/Th [17]. The Venera 9 analysis also has a non-CI U/Th ratio (Fig. 1) and is consistent with aqueous processing, and thus (possibly) be evidence for an earlier wet epoch. Sadly, V9 did not carry an XRF, and landed in a complex area of plains, tesserae, and impact materials (Fig. 2); hence we do not know what sort of rock its analysis represents.

Large-Ion Lithophile Elements. LIL elements, like alkali (Na, K, Rb) and alkaline earth (Ca, Sr, Ba) cations, are typically mobile during terrestrial aqueous

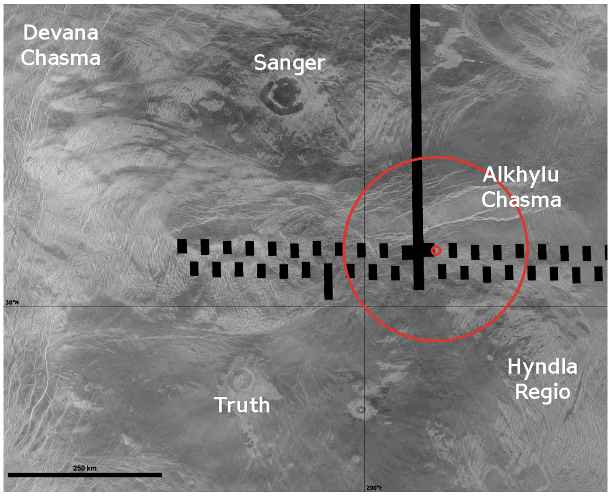

Figure 2. Venera 9 nominal landing site (31.0°N 291.6°E) and 300 km uncertainty circle (both red) on Magellan SAR image. Area is near Devana Chasma and Rhea Mons (NW of image) After [16]; see also [18].

alteration of basalt, which can lead to excesses or deficits in IAB [19]. Abundances of K were analyzed by all landers, but only Th can be used as a reference for calculating excess/deficit. Within large uncertainties, the K/Th ratios of Venus basalts are comparable to that of the Earth, except for V9 [15]. The V9 rock has a K/Th ratio about half that of Earth's mantle and OIB [15], consistent with its low U/Th ratio (Fig. 1) and suggesting that the source of the V9 rock had lost some of its original of water-soluble material.

Venus' basalts have low Ca (and Ca/Al) [15], which could represent aqueous activity. However, low Ca is also a normal character of partial melts from eclogite [15,20,21]; it is reasonable that Venus basalts could represent partially melted eclogite [13].

Abundances of other LIL elements have been useful discriminators for IAB vs OIB on Earth – Ba, Pb, Rb etc. ratioed to aqueous immobile elements like Nb [h19]. For instance, IAB tend to be enriched in Pb, Ba, and Cs [19]; we have no Venus data for these elements.

High Field Strength Elements (HFSE). The HFSE tend to be immobile in terrestrial aqueous environments, but can be affected by pressure and by oxidation state (as they can affect minerals that partition them, e.g., rutile) [22]. Pearce [23,24] showed that Ti-Zr-Y abundance ratios can be used to distinguish among MORB, OIB, and arc/continental basalts. Likewise, "The key feature of all volcanic arc basalt samples is the significant negative Nb anomaly with respect to Th and Ce…. Tholeiitic VAB is characterized also by an absolute depletion relative to N-MORB of Nb, Zr, Ti, and Y" [24]. These discriminators could be useful for Venus, backed by experimental data on how these ratios change during remelting of an eclogite or basalt.

Lander Instruments: To use these potential indicators of ancient aqueous activity, lander instruments must be able to analyze these elements at precisions and accuracies comparable to routine analyses on Earth [25]. Gamma-ray spectrometry (GRS) would seem the method of choice for U and Th (and K), measuring natural rock radioactivity as was done by on Venera and VEGA. X-ray fluorescence (XRF) is likely the method of choice for other elements, as was done also by Venera and VEGA. X-ray technology has improved enormously since then (e.g., SSD detectors), and it might be possible to measure abundances of many first- and second-row transition elements (K-Zn, Rb-Mo) and others (e.g., Ba, La, Ce). It will be critical to understand which element abundances and ratios are useful, and design spacecraft analytical instruments to accommodate that understanding [25].

Acknowledgments: To the ones who came before. Supported by NASA SSW grant 80NSSC17K0766.

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DAY-NIGHT CLOUD ASYMMETRY INHIBITS EARLY OCEAN FORMATION ON VENUS AND TELLURIC PLANETS. M. Turbet[1,2], J. Leconte[3], T. Fauchez[4,5,6], F. Selsis[3], E. Bolmont[2], B. Charnay[7], G. Chaverot[2], D. Ehrenreich[2], F. Forget[1], C. Lovis[2], E. Marcq[8], E. Millour[1], [1]Laboratoire de Météorologie Dynamique/IPSL, CNRS, Sorbonne Université, École Normale Supérieure, PSL Research University, École Polytechnique, 75005 Paris, France (**martin.turbet@lmd.ipsl.fr**), [2]Observatoire astronomique de l'Université de Genève, Chemin Pegasi 51, 1290 Versoix, Switzerland. [3]Laboratoire d'astrophysique de Bordeaux, Université de Bordeaux, CNRS, B18N, Allée Geoffroy Saint-Hilaire, F-33615 Pessac, France. [4]NASA Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, MD 20771, USA, [5]Goddard Earth Sciences Technology and Research (GESTAR), Universities Space Research Association (USRA), Columbia, MD 7178, USA [6]NASA GSFC Sellers Exoplanet Environments Collaboration. [7]Observatoire de Paris, PSL Research University, CNRS, Sorbonne Université, Université de Paris, 92195 Meudon, France. [8]LATMOS/IPSL, UVSQ, Université Paris-Saclay, Sorbonne Université, CNRS, Guyancourt, France.

Introduction: The existence of past oceans on Venus is a scientific debate now several decades old [1-8]. 1-D numerical climate modeling studies of early Venus identified clouds as the main source of uncertainty in determining the existence and persistence of ancient oceans [1-8]. Recent 3-D numerical climate modeling studies have shown that if Venus ever had surface liquid water oceans, then these oceans would be naturally stabilized by the formation of thick, reflective, subsolar tropospheric clouds [9-12].

Methods: We performed new 3-D Global Climate Model (GCM) simulations aimed at identifying the conditions for primordial surface water condensation and thus ocean formation on terrestrial planets [13]. More specifically, we performed simulations of telluric planetary atmospheres (Venus, Earth, and exoplanets) in their youth, at the end of the so-called "magma ocean" phase, during which the entire superficial water content is expected to be trapped in the atmosphere, as steam [5,14,15]. The simulations were carried out using the LMD Generic GCM (http://www-planets.lmd.jussieu.fr) a.k.a. 'LMD-G'. The model has undergone improvements in particular on convection scheme and radiative transfer [13,16] to simulate planetary atmospheres where water vapor is a major component.

Results: Our simulations reveal that clouds form preferentially on the nightside (and at high altitudes/low pressures) of young and hot telluric planets endowed with a water-dominated atmosphere [13]. These clouds therefore have a net warming effect that effectively prevents the formation of primordial liquid water oceans on the surface. This result appears to be robust in our simulations to a large set of sensitivity studies (e.g., on planetary rotation rate, water content, number of condensation nuclei).

This result has important implications for the past and present habitability of Venus, as well as of Earth and more generally of rocky exoplanets [13,17].

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Becoming Venus: How the Mantle, Volcanism, and Physics-backed Models of Global Tectonic Evolution Can Self-Consistently Explain Observations for Venus. Matthew B. Weller and Walter S. Kiefer, *Lunar and Planetary Institute/USRA, 3600 Bay Area Blvd, Houston, TX 77058 (mweller@lpi.usra.edu; kiefer@lpi.usra.edu).*

Introduction: Of all the critical questions regarding the evolution of Venus, one of the most pertinent ones regards the apparent divergence in atmosphere, surface, and tectonics between the sibling planets of Venus and Earth. Both bodies are of similar size and bulk composition, which would suggest at 1st order level that each planet would express similar patterns and styles of mantle convection, heat loss, deformation, tectonics, as well as atmospheric evolution. However, while ample data exists for the recent tectonic state of the Earth, the tectonic state, past and present, of Venus are hotly debated.

The evolutionary record of Venus is mostly unknown; however, observations reveal volcanic plains that cover and obscure > 80% of the planetary surface. While the mechanism and size/frequency of volcanic events are debated, these plains units are thought to have been emplaced within the last Gyr [1 – 3], which indicates some level of recent and perhaps ongoing volcanism. Estimates for the recent rate of volcanism, inferred from the floors of large Venusian craters [4], range from ~0.5 to 4 km^3/yr [5, 6], similar to the rate of current intraplate Earth volcanism. A thick 92 bar atmosphere, composed of ~96.5% CO_2, and surface temperatures of ~740 K are currently observed. Tectonically, the planet shows no clear evidence of Earth-like plate tectonics, which suggest Venus is either within a stagnant, episodic, or transitional regime [7 – 10]. Models of ^{40}Ar outgassing [11 - 13] in addition to a non-plate tectonic Venus, have been used to suggest that Venus is poorly outgassed when compared to Earth. Importantly, these models tacitly imply that the outgassing of the interior is not and cannot be the primary driver of the atmosphere in recent geologic time, thus requiring the atmosphere to be ‘ancient’. In contradiction to these assumptions, multiple lines of evidence directly suggest Venus once exhibited a mobile lithosphere perhaps not dissimilar to Earth [7, 10, 14], and that the atmosphere may have altered to its current oppressive state geologically recently [15].

Critically, in the past the focus has been on end member, steady-state, single plate stagnant lid behaviors or ad-hoc overturning models [e.g., 16, 17]. What these models neglected are the physical effects and the time evolution that are inherent during a change in global tectonic regimes. From both geochemical evidence and geodynamic models for the Eart, it has been shown that planets may transition between tectonic states over geologic time [e.g., 18]. Venus’ observations further bolster this idea, with the suggestion of a planet that evolved away from an Earth-like, mobile lithosphere toward a present-day stagnant-like tectonic state. Transitions are complex, but fundamentally they can occur either though a change in the buoyancy force of convection or the frictional forces operating on faults. For example, removing pore fluids [19] can serve to strengthen faults [20], whereas increasing surface temperatures reduce the buoyancy forces towards the surface that serve to drive deformation and motion of the lithosphere [18, 21 – 22]. Both changes are plausible consequences of time and planetary evolution and may operate simultaneously [10].

Here we explore the effects of a climate-driven change in lithospheric conditions on the evolution of mantle convection for Venus. From these transitioning cases, we further explore and evaluate the feedback between mantle outgassing and atmosphere generation in order to explore the feasibility of forward modeling of a global tectonic transition in order to match critical observations of the Venusian atmosphere.

Tectonic Evolution: The starting fault strengths in our experiments are chosen to be consistent with a mobile lid (of which plate tectonics is a subset). A transition in tectonic regimes is ushered in by as little as a 1-20% increase in fault strength, or a 1–15% increase in the surface temperature. Transitioning systems, from a conditionally stable mobile lid, are shown in **Figure 1**. Thirteen cases in four classes are considered; three fixed variable classes: change in yield, change in surface temperature, change in internal temperatures; and one multi variable change class. Figure 1 focuses on three different cases, two similar yield strengths and one different starting temperature for illustrative purposes (**Figure 1 caption**).

Transitions in regimes are governed by both regional and global scale instabilities, resulting in punctuated and extreme oscillations in surface mobility, internal temperatures, as well as magma production and volcanism. In the mobile lid regime, melt is generated by passive upwelling in spreading centers. In transitional states, most of the melting is plume generated at hemispheric to sub-hemispheric scales. In this state volcanism increases by $\mathcal{O}(15)$ at peak activity and decreases by $\mathcal{O}(100)$ during inactivity (relative to initial state). Melt regions become spatially diffuse and increase as the system migrates into a stagnant lid state.

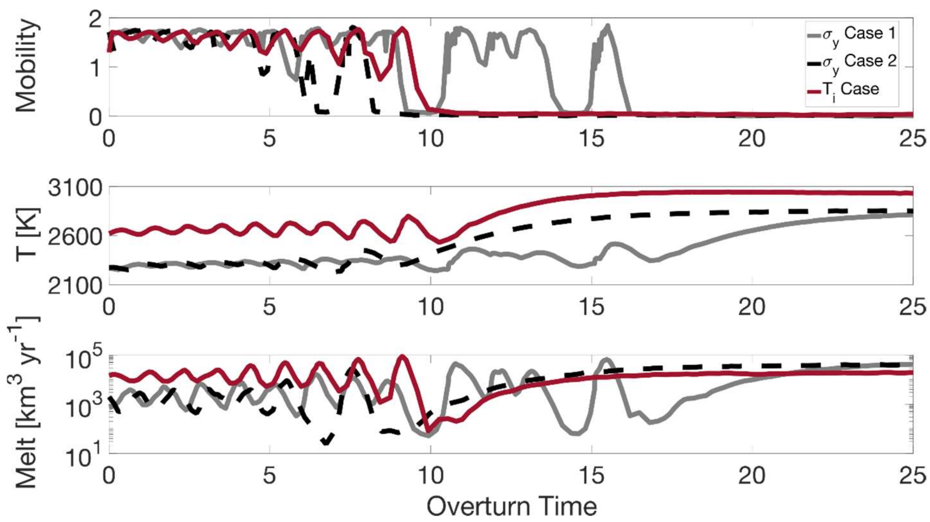

Figure 1: *Examples from coupled thermal-tectonic 3D numerical experiments (CitcomS) [23 – 24] a system transition from a mobile to stagnant lid. Panel (top): ratio of surface to internal velocity (Mobility). Mobility ≥ ~ 1 indicates a mobile lid. Mobility ≤ 0.1 indicates stagnant lid. Panel (middle): internal mantle temperatures (non-adiabatic temperature contrast is 3000 K). Panel (bottom): Melt production rate [25]. The overturn time (x-axis, all panels) corresponds to the time a parcel takes to traverse the mantle (dimensionally, an overturn time is of $\mathcal{O}$(100) Myr). Two yield strength changes (case 1 $\Delta\sigma_y$ = +8%, case 2 $\Delta\sigma_y$ = +10%) and one different temperature case (T_i case, ΔT = +15%, σ_y = -135%), are shown for illustrative purposes.*

Tectonics, Volcanism, and Atmosphere: Inherently the interior is linked to the atmosphere through volcanism and degassing [26]. For simplicity, we assume Earth-like interior compositions [27], and an initial atmosphere to be 1 Bar. We consider outgassing-only endmembers.

From the numerical simulations (**Figure 1**) surface pressure (not shown) first increases linearly in mobile lid phases due to quasi-steady outgassing rates. Upon initiation of overturn phases the atmosphere is generated in punctuated events. The total number of overturns range from 3–5 discrete events for all experiments. In each discrete overturn, atmosphere pressure increases by ~ 3 – 20 Bar in less than ~0.5 overturn times, or less than 100 million years. As the system enters a stagnant lid, melt and atmosphere generation is subdued for $\mathcal{O}$(5) overturn times. Once the system equilibrates to its new thermal state, surface pressures increase at a greater rate as compared to the mobile lid starting state.

All cases considered can generate a significant atmosphere over the simulation time of ~2.5 Gyr, the mean atmospheric generation is ~60% Venus current, but individual simulations ranging from ~19% for the highest yield cases, to ~306% for a 150 K increase in surface temperatures. Substantial volcanism can be deposited, and multi-Bar pressures can be generated over short time frames of 60 – 100 Myr. Following these rapid events, melting and outgassing is subdued for ~300 – 1000 Myr.

Observations of a thick atmospheres, current reduced volcanism, and prodigious volcanism in the past Gyr, are all consistent with models of a planet that is undergoing a transition in tectonics. During such events, Venus' surface and atmosphere would experience rapid and punctuated changes over 10–100 Myr times scales indicating that an ancient, preserved Venusian atmosphere is not needed to match observations. These results further indicate that caution should be used in overreliance on surface geology and mapping to estimate volumes of melt, as the surface only records the last dredges of an overturn event and may not reflect the true range of physical processes.

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Creating the Bridge: Melting and Volcanism In, and On, Active and Stagnant lid Planets. Matthew B. Weller and Walter S. Kiefer, *Lunar and Planetary Institute/USRA, 3600 Bay Area Blvd, Houston, TX 77058 (mweller@lpi.usra.edu; kiefer@lpi.usra.edu)*.

Introduction: The Earth is currently in a plate tectonic regime, a rarity in the solar system as Mars, Mercury, and the Moon operate under stagnant lid convection. An observation of these stagnant bodies would suggest relatively high levels of volcanism early in their evolution, followed by periods of waning volcanism, and quiescence. Similarly, observations of the Earth suggest that plate tectonics and volatile recycling are key to ongoing levels of volcanism through the present. However, critically, all the unambiguous evidence for stagnant lid convection occurs on planets substantially smaller than the Earth, and the Earth's record is incomplete and intermittent (at best) over the majority of its geologic lifetime, and particularly during its first Gyr. A pertinent question naturally follows: *Is this canonical, observed, model for long-term melting and volcanic behaviors correct for larger, ~Earth-sized, planetary bodies?*

Venus, the Earth's so-called twin, serves as a natural test case to interrogate this question. The surface of Venus consists of vast volcanic plains thought to have been emplaced within the last 300 Myr to 1 Gyr [1–4]. However, the surface record of Venus' evolution prior to ~ 1 Ga is sparse, leading to significant uncertainties and debate regarding Venus' climate, tectonic, and atmospheric history [5-10].

Without understanding how a contemporaneous near Earth-sized stagnant lid planet operates, we are ill-positioned to answer a fundamental question in terrestrial planet evolution and Venusian science*: Is Venus today consistent with a planet that has operated throughout its history as a stagnant lid [e.g., 11], or has it undergone transitions in tectonic regimes at some point in its history [e.g., 10, 12-14]?* Here we use numerical experiments of coupled 1D thermal-tectonic-convection and melting to evaluate global scale volcanic behavior as a function of endmember tectonic states for a Venus/Earth analogue planet.

Methods: *Mantle Convection*: We simulate the long-term thermal-chemical evolution of a Venus/Earth analogue planet using standard parametrized one-dimensional models of interior evolution [e.g., 15]. For these models, interior heat that is generated is required to balance the heat lost from the surface:

$$V_m\left(H-\rho_m C_m \dot{T}_m\right)-\rho_m f_{pm} L_{pm} = A_c Q_c - A_s Q_s \quad (1)$$

where V_m is the mantle (subscript m) volume, C_m is the heat capacity, ρ_m is density, $\dot{T}_m$ is the time average change in the temperature, H is radiogenic heat production (here assumed to be initially chondritic), L_{pm} is the latent heat of melt, f_{pm} is the melt production, A is area and Q is heat loss from the core (subscript c) and from the surface (subscript s). A simplified version of equation (1) is used to track the evolution of a single layer core.

For the mantle, the Nusselt number (Nu) is given by a Nusselt-Rayleigh (Ra) relationship [e.g., 16, 17], and the viscosity (η) which is dependent on the temperature, pressure (p), water content (fH_2O) and melt fraction (φ), are defined as:

$$Nu \sim (Ra)^{\beta} \quad (2)$$

$$Ra = g\rho\alpha\Delta T d^3/(\kappa\eta) \quad (3)$$

$$\eta(T_m, p, H_2O, \phi) = A_0 fH_2O \exp\left(\frac{E+pV}{RT_m}-\gamma\phi\right) \quad (4)$$

where α is the thermal expansivity, g is the Venusian surface gravity (for simplicity), κ is thermal diffusivity, d is the Venusian mantle thickness, A_0 and γ are empirical constants, R is the universal gas constant, and E and V are the activation energy and volume, respectively. The exponent β is set to 0.33 (active lids) and 0.2 (stagnant lids) [16, 17]. We use standard solidus and liquidus relationships to track melting, modified to allow for the effects of water and depletion [18–20]. All simulations assume 20% extrusive melt. While these simulations employ a deep-water cycle [e.g., 18], for simplicity and to determine general behaviors, regassing is disallowed.

Tectonic state, melt, and volcanism: For a planet within a plate tectonic-like regime, the vast majority of volcanism occurs through decompression melt at mid-ocean ridges. Melt production simply follows as:

$$f_{pm} = \phi^* \cdot D_{melt} \cdot S_{pr} \quad (5)$$

where ϕ^* is the melt fraction, and D_{melt} is the depth of the melting layer, which changes over time. The spreading rate of the mid-ocean ridges follows as: $S_{pr} = 2 \cdot MOR_L \cdot u_c$, where MOR_L is the ridge length and u_c is the convective velocity [18, 21]. MOR_L is assumed to be both constant with time, and to scale as the change in surface area between Earth and Venus.

Convection within a stagnant lid planet is often dominated by regions of passive upwellings and downwellings, which stands in contrast to the much more active convection of a plate tectonic-like system. Passive upwelling velocities are approximately proportional to the velocity of the interior (u_i), such that $u_i < u_c$. Melt production follows from [22]:

$$f_{pm} = \frac{4 \cdot u_i \cdot \phi^* \cdot (D_{melt})^2}{d^2} A_s \quad (7)$$

Results: Early plate tectonic-like active lids generate substantial melt of $\mathcal{O}$(800) km^3/yr. The early enhanced period of melt production, where melt is localized and efficiently channeled along volcanic ridges, leads to substantial heat loss, rapid convective velocities, and subsequent cooling of the interior. Though the interior is colder after this phase, decompression effects, and a relatively shallow lithosphere, allow for melt production to continue through the remainder of the numerical experiment, however at a reduced rate.

In stark contrast to active lids, early stagnant lid convection initially generates negligible melt $\mathcal{O}(0.3)$ km^3/yr. Compared to the active lid regime, this reduction in melt is due in part to the initial thicker lithosphere of the stagnant lid. This suppresses decompression melt to greater depths, which in turn requires a larger increase in temperature to cross the solidus. Relatively low convective velocities further limit the amount of material that can flux through the decompression zone. Melt transport through the thick and relatively intact lithosphere is considerably less efficient.

From 1.1 to 1.8 Gyr (dependent on initial T_m and T_s), melt production in the stagnant lid intersects and is indistinguishable from active lid cases. This condition holds through the remainder of the numerical experiment, with the stagnant lid melt production curves matching active lid melt production curves at higher initial T_m and T_s conditions. By ~6 Gyr, despite differing lid states and internal temperatures, both the heat flux and melt production will be effectively indistinguishable, though stagnant lids become increasingly more efficient volcanic producers, though melt production in the stagnant lid is largely constant.

Key implications for early plate tectonics-like behavior are substantial and decreasing melt production over the first Gyr, followed by monotonic decreasing production (and plate speeds) over the next 9 Gyr. Stagnant lid melting behaviors may effectively be constant with time, and lower. After ~ 1 -2 Gyrs, volcanic rates between the cases are indistinguishable, and after ~6 Gyrs, heat flux, volcanism, and plate speeds, may not be sufficient to distinguish between tectonic states.

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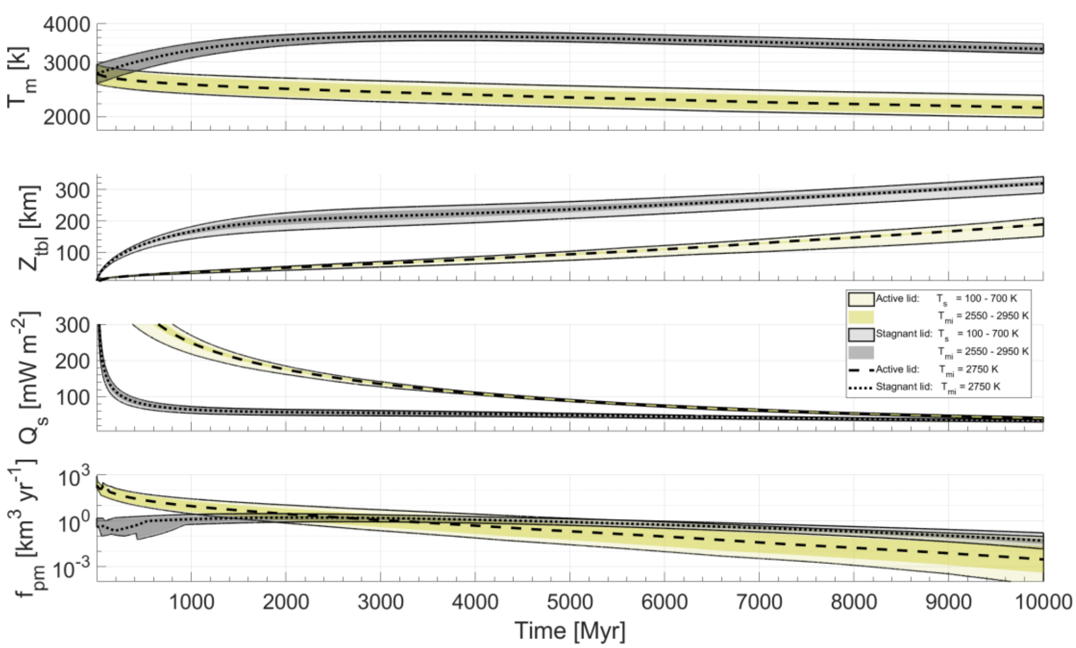

Figure 1: *Output examples from 1D numerical simulations. Panel (top): Mid-Mantle temperatures. Panel (second): Thermal boundary Layer Thicknesses (Z_{tbl}). Panel (three) Surface Heat Fluxes (Q_s). Panel (bottom): Melt production (f_{pm}). The yellow field indicates plate tectonic-like active lids results, the grey field indicates stagnant lid results. Central colored regions show ranges of initial mantle temperatures (T_{mi}), lighter colors with solid outline indicate effects of surface temperatures (T_s).*

TESSERAE: IDENTIFYING DISTINCT DEPOSITS USING SURFACE ROUGHNESS CHARACTERISTCS DERIVED FROM MAGELLAN DATA. J. L. Whitten[1] and B. A. Campbell[2], [1]Department of Earth and Environmental Sciences, Tulane University, New Orleans, LA (jwhitten1@tulane.edu), [2]Smithsonian Institution Center for Earth and Planetary Studies, MRC 315, Washington DC.

Introduction: Tesserae represents some of the most ancient materials on Venus and, as such, preserve the longest record surface evolution on the planet. This is particularly exciting if Venus had a much different climate in its past [1] that was recorded by these ancient rocks. Results from the Venus Express mission hint at a more silicic composition for tesserae [2, 3], a possible indicator of large volumes of surface water earlier in Venus' history.

Compositional information is not yet available for Venus, so many researchers have been using Magellan synthetic aperture radar (SAR), topography and emissivity datasets to characterize tesserae [e.g., 4, 5, 6]. Tesserae are highly deformed materials with at least two intersecting sets of tectonic structures [4]. They appear radar-bright owing to their high surface roughness at the lengthscale of the Magellan radar signal (12.6 cm). Here, we analyze SAR data to explore the statistical distribution of radar backscatter power to draw conclusions about the diversity of Venusian tesserae .

Methodology: SAR left-look data from the Magellan mission were used to derive backscatter coefficient [7] for 22 tesserae across Venus. Data were extracted from near the crestline of away-facing (east-facing) ridge slopes. Sampling near the crestline was meant to avoid boulders and sediment mass wasted into valleys.

Backscatter coefficient values: There is a lot of variability in the backscatter coefficient values of the mapped tesserae, with backscatter range from approximately -30 dB to 13 dB. Average backscatter behaviors suggest that the variations observed between tesserae are relatively small, with a total range in average backscatter of only ~6 dB. The largest backscatter values tended to be associated with tesserae at high elevations, above the "snow line" or ~6053 km planetary radius [8].

Impact crater ejecta appeared to have a strong effect on backscatter coefficient values, changing backscatter by ~2.5 dB (Fig. 1). This difference in backscatter is the same as the difference in the average value between Alpha and Fortuna tesserae. One notable example is at Husbishag Tesserae, where the distribution of backscatter coefficient values for tesserae within and exterior to the ejecta from Boulanger crater is different. There is a notable decrease in backscatter coefficient values, ~1.5 dB, within the impact crater parabola, which is clearly visible in the Magellan SAR images.

Classifying Tesserae: Measured backscatter coefficient distributions in the tesserae are significant and imply real differences between these deposits. Only a few processes other than surface roughness have been identified to explain backscatter variations, including high reflectivity materials at high elevations and impact crater ejecta. The remaining variations in backscatter coefficient are interpreted to be due to decimeter-scale roughness variations. Calculating the deviation of tesserae from a mean backscatter coefficient value

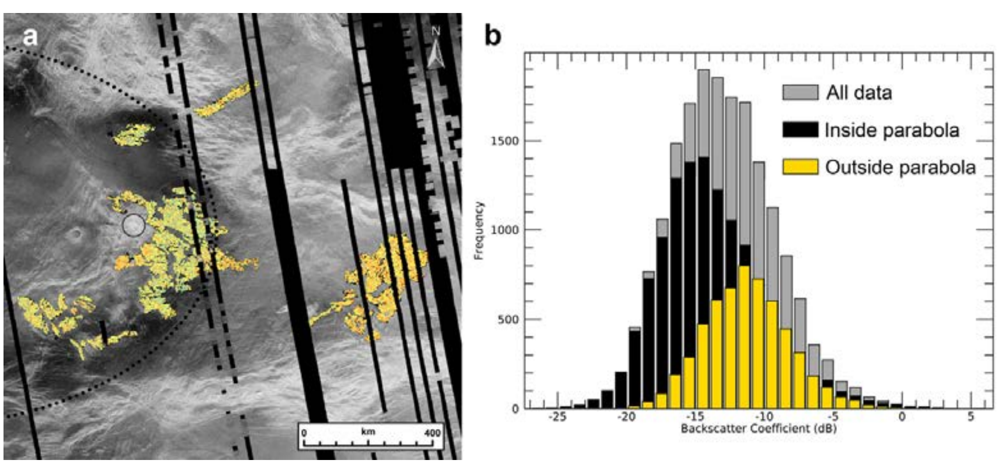

Figure 1. Influence of crater ejecta deposits on the backscatter coefficient of tesserae. (a) Husbishag tesserae backscatter values (colored dots). Boulanger crater (~74 km in diameter; black circle) impacted just west of Husbishag and its parabolic ejecta extent (dotted black line). (b) Histogram of backscatter values for all of Husbishag (gray), just points within the crater parabola ejecta (black), and those outside of the crater ejecta (yellow).

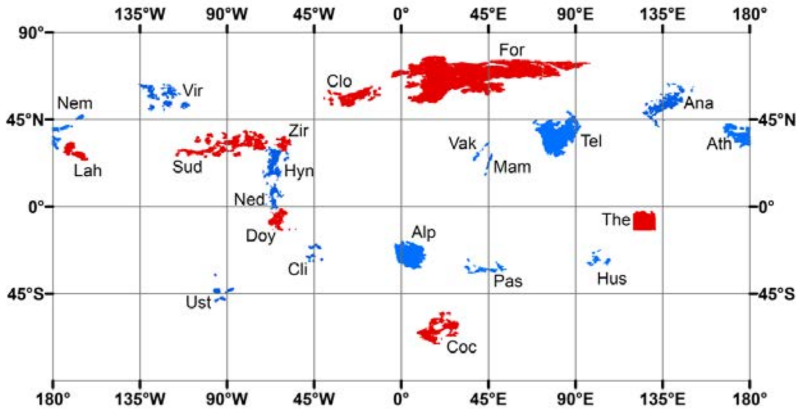

Figure 2. Classification of twenty-two tesserae based on their cm-scale roughness characteristics. Blue polygons represent tesserae that have smoother-than-average slopes and red polygons indicate tesserae deposits with rougher-than-average slopes. Tesserae are labeled using the first three letters of their official names (e.g., For = Fortuna).

allows a classification to two major types (Fig. 2). There is no obvious spatial clustering of these two classes of tesserae, with each class occurring across a wide range of latitudes and longitudes.

Conclusions and Future Work: Tesserae can be divided into two groups: deposits that are smoother than average tesserae and those that are rougher than average. This result presents a different framework to assess tesserae and provides groupings that are distinct from other analyses of Magellan data [5]. These two groups emphasize that post-emplacement processes play an important role in the surface evolution of tesserae, with crater ejecta deposits producing significant changes to cm-scale surface roughness. Despite the influence of crater ejecta, real significant differences have been identified. For instance, the variations in cm-scale roughness for certain tesserae (e.g., Fig. 2) point to further differences in these deposits. Current results indicate that upcoming missions will have to consider the presence of crater ejecta and other transported sediments when evaluating the rock types and diversity of tesserae.

Future work involves filtering the backscatter coefficient data to remove roughness values that overlap with suspected parabola locations to further characterize "uncontaminated" tesserae and add subdivisions to the classes presented in Figure 2. All crater >11 km are expected to produce parabolic ejecta deposits, thus a significant portion of the surface of Venus, including tesserae, may have been covered with ejecta (Fig. 3). These tesserae will be analyzed further to assess the roughness characteristics of uncontaminated tesserae and how varied these materials may be on Venus.

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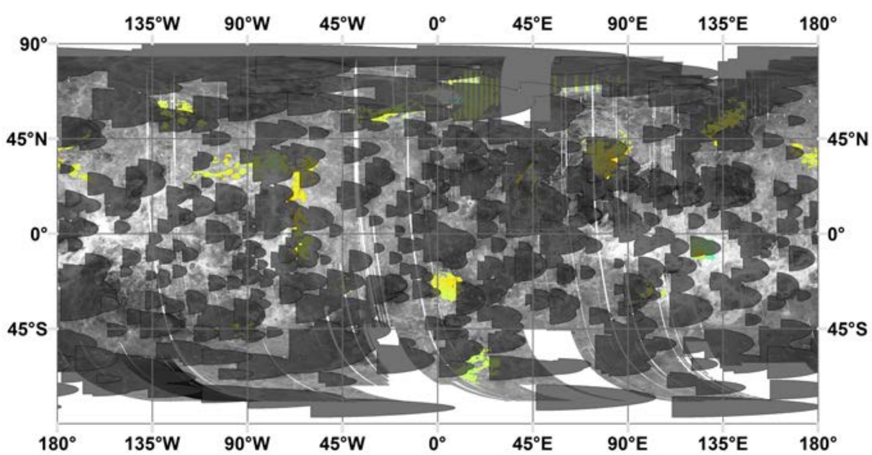


Figure 3. Distribution of ejecta parabolas [from 9] overlaying backscatter coefficient measurements.

ANCIENT GASES OF ANCIENT VENUS. K. J. Zahnle[1], [1]Planetary Systems Branch, Space Sciences Division, NASA Ames Research Center (Mail Stop 245-3; Kevin.J.Zahnle@NASA.gov).

Introduction: The noble gases are the passive bystanders of planetary evolution. They are shunted into the atmosphere, and often as not thrust into space, never to return. Those that remain preserve a sparse but relatively accessible record of the planet's entire history. Given the difficulty in obtaining access to other records, they are likely to play an outsized role in the retelling of Venus's story for the foreseeable future.

Nonradiogenic noble gases: The least expected major discovery made in the first wave of *in situ* Venus exploration was a great abundance of nonradiogenic argon (^{36}Ar and ^{38}Ar) and neon, possibly extending to krypton (see Figure 1). *Viking* on Mars had found that bulk Ar/N and Ar/CO_2 ratios were Earth-like, and it was therefore hypothesized that Ar is a tracer of planetary volatile abundances[1]. Hence, as Venus has similar bulk CO_2 and N_2 inventories as Earth, it was expected that Venus would have a similar amount of Ar. The prediction was made just in time to be found wrong. It turns out that nonradiogenic Ar is 70 times more abundant on Venus as on Earth. Neon is similarly enriched on Venus; krypton may or may not be, depending on which measurement one accepts. Data for Xe are reported as upper limits.

It is sometimes suggested that the Venerian noble gases were acquired directly by gravitational capture of solar nebular gases. Such a story is reasonable in general, and there may prove many examples of such amongst the exoplanets, but it does not work for Venus without special pleading. Venus's Ne/Ar ratio is only 1% that of the Sun. Indeed, Venus shares the same Ne/Ar ratio as Mars, Earth, and the chondritic meteorites. Even more telling, the bulk abundances of Venus's Ar and Ne are quite similar to what is seen in the chondritic meteorites (Figure 1). What this means is that Earth, not Venus, is the outlier. Something happened to Earth. The leading explanation for the general depletion of noble gases on Earth (and to even greater degree, Mars) has to be impact erosion at the end of accretion at a level of efficacy not seen by Venus [2]. Genda & Abe's argument is that Earth was more susceptible to impact erosion because its water was condensed and its CO_2 in rocks, and such were not the case for Venus. This sets an important boundary condition on ancient Venus: its atmosphere was deep and thick and its oceans (if any) were vapor and its CO_2 was mostly in the atmosphere as it is today[2].

Nonradiogenic noble gas isotopes: Much of the most interesting information in the noble gases is preserve in their isotopes. This includes provenence, and in the case of Xe and possibly Ne and Ar, evidence of historic escape.

Neon. Generous error bars render previous spacecraft measurements of ^{20}Ne/^{22}Ne unable to distinguish between a solar (~13.6) or planetary (~10) ratio. Neon is potentially subject to escape as a neutral in vigorous hydrodynamic hydrogen escape. However, hydrodynamic escape does not fractionate Ne strongly unless the bulk atmosphere contains a great deal of CO or N_2.

Argon. Generous error bars render previous spacecraft measurements of ^{36}Ar/^{38}Ar unable to distinguish between a solar (~5.5) or planetary (~5.3) ratio. Like Ne, Ar is potentially subject to escape as a neutral in vigorous hydrodynamic hydrogen escape. In principle hydrodynamic escape can fractionate Ar strongly if the bulk atmosphere is mostly CO_2. This may have happened on Mars where gravity is weak. However, very vigorous CO_2-throttled escape would only be possible from Venus when the Sun was very young, and the reported ^{36}Ar/^{38}Ar ratio does not leave much scope for hope here.

Krypton. Krypton isotopes carry subtle signatures in other solar system bodies (see Figure). In principle, Kr isotopes are the hardest to change by planetary evolutionary processes and hence the best indicators of provenence. However (not unexpectedly) differences between different kyrptons are small. Unless there is something astonishing about Venus, one expects little from Kr until we have a sample return mission.

Xenon. Xenon is the lord of the isotopes. Nine are stable. Xenon's two lightest isotopes are rare and will not be measured short of sample return, but the other seven are potentially measurable by a probe *in situ* and are packed with information. Here we focus on escape.

Evidence that Xe has escaped from Earth is strong. (i) The isotopes of nonradiogenic Xe are strongly mass fractionated, easily seen in the Figure. (ii) Xe is depleted in air by a factor of 4-20 compared to Kr, also obvious in the Figure. (iii) Radiogenic Xe is much less abundant than it should be compared to solar system abundances of the extinct parents. About 7% of air's ^{129}Xe derives from decay of ^{129}I (15.7 Myr half life), which is only 1% of what a planet of Earth's mass with Earth's iodine content would have, had none escaped [3]. About 4.5% of air's ^{136}Xe derives from spontaneous fission of ^{244}Pu (half life 80 Myr). This is roughly 20% of what is expected given the primoridal abundance of ^{244}Pu [3]. It therefore seems that Xe escape was taking place from Earth at least 200 Myrs into the life of the solar system.

More recent work shows that Xe escaped from Earth for 2 Gyrs. Xenon recovered from Archean and early Proterozoic (2.4-3.5 Ga) rocks is less strongly mass fractionated than Xe today [4]. Fractionation is least in the oldest samples, and reached modern levels when the atmosphere became oxidized ca 2.4 Ga [4].

That Xe escaped and Kr did not makes it likely that Xe escaped as an ion [5]. This works because Xe is more easily ionized than H or O, whilst Kr is more difficult to ionize than H and O. As an ion, Xe's cross section to other ions is very great. Hence Xe can be swept off as an ion in a photo-ionized hydrodynamic wind comprising H and O, but neutral Kr stays behind.

We identified several limiting factors required for Xe to escape as an ion from Earth. (i) the Sun needs to be a strong enough source of EUV radiation. (ii) there needs to be enough hydrogen that Xe^+ ions can be swept off by protons. (iii) there needs to be a planetary magnetic field, which is required to organize a polar wind. (iv) There cannot have been abundant O_2, which charge exchanges with Xe.

What then should be expected of Venus? There is no particular reason to expect a pattern similar to what we see on Earth or Mars. It is possible that no primordial Xe remains from the early loss of Venus's oceans; certainly there would be enough EUV and hydrogen. However, if there were no magnetic field, the Xe might relatively unscathed.

Radiogenic noble gases: Radiogenic ^{4}He (from Th and U decay) and ^{40}Ar (from ^{40}K, 1.25 Gyr half-life) chronicle the long story of mantle degassing, whilst radiogenic xenon -- descended from parents long extinct – is most pertinent to early planetay evolution.

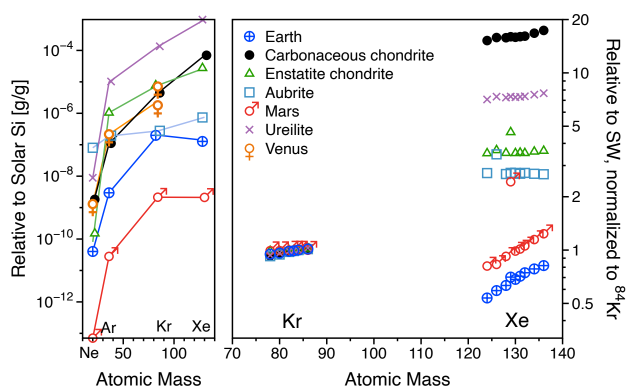
A surprise from the first wave of Venus exploration was a relative dearth of radiogenic ^{40}Ar. Venus has only about a quarter as much ^{40}Ar in its atmosphere as Earth. If Venus has a similar amount of potassium as Earth, this means that 7/8ths of its ^{40}Ar still remains within the solid planet. There has been a failure of outgassing. This could be ascribed to a general failure of volcanism, or it could be ascribed to a lack of a carrier. ^{40}Ar is not itself abundant enough to form bubbles efficiently, but rather it partitions into bubbles formed by more abundant volatiles, such as CO_2. If bubble-forming volatiles are already in the atmosphere, ^{40}Ar degassing would be suppressed.

Helium does not currently escape from Venus. Helium escapes from Earth in a polar wind shepherded by the planetary magnetic field. Helium escape from Venus is inhibited by the low temperature of the upper atmosphere (a consequence of radiative cooling by abundant CO_2), or the absence of a magnetic field, or both. To the extent that it degasses, radiogenic helium should have built up in the atmosphere for as long as CO_2 has been abundant and the magnetic field absent. The ^{40}Ar/^{4}He ratio becomes a powerful tool for reconstructing the planet's story. Unfortunately, the solar wind can also be a significant source of helium. Distinguishing between solar and degassed helium requires measuring the ^{3}He/^{4}He ratio.

Xenon's radiogenic isotopes provide clocks pertinent to Venus's first 500 Myrs. As Venus and Earth will not have accreted in lockstep, it is reasonable to expect that the ^{129}Xe abundance on Venus should be quite different form that of Earth. The iodine clock resolves events occurring in the first 100 Myrs. The plutonium clock comes from spontaneous fission, which spreads daughters across Xe's heavier isotopes. This makes for a difficult measurement, as ^{244}Pu was never abundant. But if fissiogenic Xe can be measured, it provides another clock for the first few hundred Myrs.

References: Use the brief numbered style common in many abstracts, e.g., [1], [2], etc. References should then appear in numerical order in the reference list, and should use the following abbreviated style:

[1] Anders E. and Owen T. (1977) *Science, 198,* 453-465. [2] Genda H. and Abe Y. (2005) *Nature 433,* 842-844. [3] Pepin R. O. (2006) *EPSL, 252*, 1-14. [4] Avice G. et al. (2018) *GCA, 232,* 82-100. [5] Zahnle K. et al. (2019) *GCA, 244,* 56-85.



Noble gases. The left panel shows the elements normalized against the solar abundances, in units of Si to honor our new masters. Note that, to the extent that these things are known, Venus quantitively resembles chondritic meteorites, whilst Earth and Mars are depleted. The right panel shows Kr and Xe isotopes compared to the solar wind, normalized to ^{84}Kr. Depletion and mass fractionation of Xe on Earth and Mars are obvious. Note that no data for Venus are shown, as none exist.