VENUS AS AN EXOPLANET LABORATORY: THE MANY PATHWAYS TO VENUS-LIKE EXOPLANETS AND HOW TO MAKE ENDS MEET. James W. Head¹, Stephen R. Kane², Robin D. Wordsworth³ and Stephen W. Parman¹, ¹Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI USA (james hea@brown.edu), ²Department of Earth and Planetary Sciences, University of California, Riverside, CA USA, ³School of Engineering and Applied Sciences, Harvard University, Cambridge, MA, USA.

Introduction: Sixty years of Solar System exploration has provided new insights into the reality of the multiple pathways of planetary formation and evolution that can be applied to the exploration of exoplanets and other planetary systems. In this contribution we focus on how our current knowledge of Venus can be applied to interpret and understand the family of currently known Venus-like exoplanets [1]. What key questions can we identify that will aid us in interpreting the extremely large parameter space represented by the presence of dozens of Venus-like planets occurring in multiple planetary systems around other stars?

Current Knowledge: We know several things about the nature of Venus, and these represent “temporal bookends” on its history and evolution. At the earliest end, we rely on models for the formation and early evolution of Venus based on planetary evolution analogs, and the possibility of a water-rich early history with the presence of oceans, based on Pioneer/Venus D/H data [2]. At the most recent end, we know the general nature of its current “runaway greenhouse”-like, CO₂-dominant atmosphere, and the geologic processes and sequence of events representing the most recent 10-20% of its history [2,3]. The nature of the intervening period of evolution of the interior, surface and atmosphere, the majority of the history of Venus, is unknown. What are the different pathways between these bookends? How can they be predicted and distinguished, and used as a guide to the exploration and understanding of Venus-like planets in other planetary systems? In turn, how can the observed array of Venus-like exoplanets inform us of the candidate pathways that might have characterized the missing chapters in Venus’ history?

Working Backward in Time: Global data from the Magellan Mission enabled construction of a global geologic map [3] and a synthesis of the nature and sequence of volcanic and tectonic processes operating there. These data showed that 1) there was a paucity of superposed impact craters, 2) the average age of the surface was less than a billion years, 3) the crater population was not easily distinguishable from a spatially random one, 4) most craters were not significantly modified, and 5) there was no evidence of active plate tectonics. Detailed and global geologic mapping of stratigraphic sequences showed that the geological history of Venus can be characterized by three basic consecutive phases: Phase I represents the period prior to the formation age of the geomorphological/geological units on the surface and occupies the majority of the history of Venus. The observed geologic record starts with Phase II, comprised of two regimes, an initial global tectonic regime interpreted to have formed the tesseræ (~7.3% of Venus). The second regime in Phase 2, the global volcanic regime, starts with emplacement of volcanic plains dotted with thousands of small shield volcanoes, and is immediately followed by regional plains interpreted to have been emplaced as flood basalts (~61.3%). Thus, the vast majority of the observed surface geologic units on Venus (80.7%) formed over a relatively short period of time. Phase III represents a distinctive change in style, an extended period of global network rifting; volcanism continues to today [4], primarily characterized by lobate lava flows associated with the rifts. In summary, the geological record consists of the majority of history that leaves no geological/geomorphological record (Phase I), followed by Phase II, a period of intense global tectonic deformation and global volcanic resurfacing over 60% of the planet, followed by Phase III, relative quiescence and development of a global rifting system linking several broad rises. Although active plate tectonics was not observed, the young age of the surface of Venus strongly suggested that a significant global change had taken place. Each candidate model to explain the transition in geologic and geodynamic history from the observed record back in time (Fig. 2) has significant implications for the atmosphere. 1) Equilibrium volcanic resurfacing called on random volcanic resurfacing to bury craters and constantly maintain an average crater surface age; no unusual inputs to the atmosphere were envisioned. 2) Global volcanic resurfacing that ended abruptly was called on to explain the obliteration of previous craters and the preservation of observed craters; this would clearly be accompanied by extremely high fluxes of volcanic gases. 3) Volcanic heat-pipe mechanisms on a one-plate planet were suggested to explain the observations; this would imply a constant and significant input of volcanic gases into the atmosphere. 4) A uniformitarian-evolutionary temporal change from mobile-lid to stagnant lid convection was called upon to explain the lack of plate tectonics in late Venus history; this would imply a cessation of recycling of crust into the mantle (possibly including ocean-related volatiles in earlier history), and resulting changes in rates and types of vol-
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canic inputs into the atmosphere. 5) Catastrophic episodic model called on either episodic vigorous plate tectonics or global overturn of a depleted mantle layer, leading to intense crustal deformation rapidly followed by massive fertile mantle upwelling, melting and a pulse of global volcanism, followed by relative quiescence; the catastrophic global outpouring of lava would have significant input into the atmosphere.

Critical Outstanding Questions: We now identify a series of fundamental questions that can help guide an improved understanding of the multiple pathways that might have been taken by Venus throughout its evolution. We focus on those questions that might have specific predictions about the nature of the atmosphere and climate, and those that can aid in the development of observational and instrumental strategies for the discovery and understanding of Venus-like exoplanets. 1. Current Atmosphere: What is the cause of the current “runaway greenhouse” state of the atmosphere of Venus? What are the distinctive signatures of this current atmospheric and climate state that might be recognized in exoplanets? 2. Atmosphere-Surface Buffering: What is the range of atmosphere-surface processes that can buffer the current atmosphere and what is their predicted stability? 3. Recent Phase III Geological History: Is the geologically recent rate of volcanism (Phase III) inferred from the geologic record sufficient to maintain the atmosphere in its current state? Over what time scales? If volatile input into the current atmosphere is episodic, what rates and repose periods are required to maintain its stability? 4. Recent Phase II Geological History: Is the degassing associated with the geologically rapid global volcanic resurfacing observed in Phase II sufficient to produce the currently observed atmosphere? If so, does this provide clues to the more detailed nature of the resurfacing event? If not, does this provide clues to the nature of the ambient atmosphere before the Phase II event? If the intense crustal deformation implied by the Phase II tessera formation exposes voluminous fresh bedrock, what is the effect on atmospheric buffering? 5. Nature of the Venus Mantle: What is the parameter space predicted for the Venus mantle for composition, convective style, petrogenesis, percent partial melting, volatile content and volatile release? 6. Ancient Phase I Geological History and Pathways to the Present: What are the petrogenetic processes, characteristics, outgassing rates and pathways predicted for the following plausible states for the Phase I history of Venus: a) one-plate planet dominated by vertical accretion of secondary crust; b) episodic global overturn of vertically accreting secondary crust, accompanied by upwelling and pressure-release melting of fertile mantle; c) mobile-lid plate tectonics regime with subduction, and with and without oceans; d) episodic plate tectonics and/or depleted mantle layer overturn; e) Io-like advective hot-spot heat loss with distributed centers of volcanism; f) sequential combinations of the above? Which pathways can account for the Pioneer-Venus D/H ratios? 7. Stochastic Processes: What is the role of stochastic processes? What are the effects of basin-scale impact processes on the formation, retention and characteristics of primary and secondary atmospheres? What is the effect of cometary inputs to the atmosphere instantaneously and over time? Can any of these signals be recognized in the residual atmosphere? 8. Integrated Atmospheric and Climate History: How do each of these multiple states contribute to the origin and evolution of the atmosphere? What is the most likely sequence for the history of Venus? Which of these states produce unique atmospheric signatures that might be recognized on Venus-like exoplanets? How does atmospheric structure/composition influence atmospheric loss rates? 9. Habitability: Which of these states and evolutionary sequences might be most conducive to the formation and evolution of life? Are any unique or distinctive signatures of these states and pathways predicted for the atmosphere? 10. Relation to Earth History: What lessons for Venus can be learned from the evolving understanding of Earth history? 11. Implication for Venus Exploration: How can these fundamental questions guide the current and future exploration of Venus? What are the outstanding questions that can be addressed on decadal timescales? 12. Implications for Exploration of Venus-like Exoplanets: What are the distinctive and unique atmospheric signatures that might be associated with these multiple pathways, and how can these be applied to the exploration and demographics of Venus-like exoplanets?


Fig. 1. Venus transitional scenarios (References in 3).