Venus: a Natural Volcanological Laboratory

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Introduction: Volcanism is a fundamental process of planetary evolution. Volcanism, encompassing the melting of material via internal heat, generally in convecting planetary mantles, and the ascent of such material to become intrusive (subsurface) and extrusive (surface) contributions to planetary crusts, constitutes a primary expression of a planet's physical, thermal, and chemical evolution. Thus, volcanic features preserved at a planet's surface offer fundamental clues to a planet's history. The imaging and topography data collected by NASA's Magellan Mission enabled enormous strides in advancing our understanding of volcanism on Venus. However, progress inevitably reveals new mysteries and leads to new questions that are at or beyond the limits of the available data to resolve. Here I identify the next steps that would unleash the potential of the vast range of volcanic phenomena recorded at the surface of Venus to inform, or perhaps transform, studies of Venus' evolution and the volcanic expressions of inner solar system bodies in general. Here I focus on "physical volcanology" phenomena and how our understanding of Venus volcanism can be revolutionized by collecting imaging and topography datasets with increased resolution (these are within our grasp!). To be sure, the geochemical and petrological aspects of volcanism are also vital components to unraveling the "big picture" of Venus evolution, and I expect such issues will be covered in other contributions.

What makes Venus a Natural Volcanological Laboratory? 1) Diversity. The surface of Venus is replete with manifestations of magmatic/volcanic activity [1, 2] across a vast range of spatial scales. A prominent review of the post-Magellan state of the field [2] summarized this range by defining the following useful categories: 1) Volcanic Rises and Major Volcanic Provinces, 2) Large Volcanoes (diameter $D > 100$ km), 3) Intermediate Volcanoes ($D < 100$ km), 4) Small Volcanoes, Small Shields with $D < 20$ km, and Shield Fields, 5) Calderas, and 6) Centers of Large Flow Field Eruption. These workers listed 167 Large Volcanoes (for example, Sif Mons in western Eistla Regio, Fig. 1a), defined as centers of eruption with diameter greater than 100 km displaying "lava flows centered on a region of current or former positive topography as indicated by multiple lava flows radially distributed over 360° of azimuth" [2]. Radial flows are a distinctive feature of large Venus volcanic edifices, with only a handful (example: Tepev Mons in Bell Regio, Fig. 1f) displaying evidence for diversion to circumferential directions indicating filling of a distal annular topographic depression indicating lithospheric flexure (the "flexural moat" [3, 4]. Flows confidently associated with edifices constitute 5% of the surface area of Venus, but it is unclear what fraction of units distinguished as "plains flows" (a much larger fraction of Venus' surface) have origins at large edifices [2].

There are several additional categories of large volcano-tectonic centers on Venus. Coronae are volcano-tectonic structures characterized by annular zones of fractures and/or topographic highs [Stofan Coronae]. Consider Aruru Corona (Fig. 1b), located south of Asteria Regio within the particularly active "Beta-Atla-Themis (BAT) Triangle" Over 360 such features have been identified with diameters ranging from 75 to 2000 km [5]. They have a size distribution that overlaps that of Large Volcanoes, and a significant number of constructs are identified on lists of both volcanoes [2] and Coronae [5] (Aruru Corona is one such multiply classified construct), demonstrating that a significant fraction of coronae have a substantial constructional volcanism component [e.g., 6, 7]. However, it is clear that response to upwelling and spreading viscous flows of mantle and lower crustal material plays key roles in the development of corona structures [e.g., 5], particularly in rift settings and at larger sizes. It is

evident that the morphological class “corona” contains features originating from a wide range of physical mechanisms [e.g., 7], and sorting these out requires advances in data resolution.

Several classes of volcanic features on Venus are influenced by dominant signals of intrusive activity, or emplacement of magmas at depth in the crust/lithosphere. For example radiating fracture systems [8], typically of hundreds of km in lateral extent, likely result from emplacement of dike swarms. The stellate nature of “starburst” patterns led to the coinage “nova” for some such features [1]. Generally smaller features with combinations of radial and concentric fractures resembling terrestrial invertebrates and have been designated “arachnoids” [1]. It is important to note the large degree of overlap of features classified as “radiating dike systems”, “large volcanoes”, “coronae”, “arachnoids”, etc. Such overlaps indicate that establishing clear categories with meaningful distinctions for origin and evolution is difficult at present. Some of this likely reflects the inherent complexity of real volcanic systems (which is wonderful!), but there is also an indication here that we currently lack the data required to render more confident assessments of these features.

What makes Venus a Natural Volcanological Laboratory? 2) Preservation. The large numbers, broad range of sizes, and morphologic variety of volcanic features relative to Earth's volcanic record can be understood when viewed through the lens of Venus' distinct evolutionary path. For Earth-sized planets, high levels of internal heat have been preserved over the age of the Solar System, thereby allowing large-scale manifestations of volcanism to persist over that span, obviously for Earth and quite likely for Venus. However, the vigorous process of plate recycling on Earth, part of the system of plate tectonics, removes or alters and deforms much of this evidence, either by subduction of oceanic crust or repeated cycles of continental collision. Because Venus lacks a global plate tectonic system [11] (again, at present and in the discernible past), Venus volcanic features avoid deformation and even utter destruction by global-scale tectonic processes. Further, because Venus lacks an ocean (at present and in the discernible past), Venus volcanoes are relatively unaltered and unobscured by geological processes such as erosion, sedimentation, and mass wasting. Due to accumulation and preservation of numerous examples of volcano-tectonic evolution over the timespan recorded by the currently observable geologic record (hundreds of millions of years [12]), Venus can be thought of as a natural laboratory for the study of volcanism and volcano-tectonic interactions.

Venus preserves important manifestations of basaltic volcanism that are hard to preserve on Earth. Given that the thick silicic crust of Earth's continents complicates the expression of plume related volcanism (producing high-viscosity magmas and explosive activity that generate narrow and steep stratovolcanoes, vs. the effusive low-viscosity basalts that build broad gently sloped shields), the best volcanic analogues to the basaltic planets are the ‘hotspot chain’ volcanoes that form on the thin basaltic crust of the oceans. The largest manifestations of mantle plume activity on Earth are the Large Igneous Provinces (LIPs), thought to result from vigorous melt generation at the head of a fresh mantle plume [e.g., 10]. Many of these end up getting mashed up with continents during plate collisional events, and others remain on oceanic crust (beneath several km of ocean and buried by sediments) while being carved up by mid-ocean ridges, with the pieces transported in several different directions! On Venus, these “bad influences” are not present, and volcanoes and the broader volcanic rises on which they sit [13] remain exposed as clues to the interior processes that drive magmatism. The upshot is that Venus preserves “Hundreds of Hawai’is” and numerous rises that reflect processes often difficult to observe on Earth.

Figure 1. Large volcanic structures on Venus (except where otherwise specified). (a) Sif Mons. (b) Aruru Corona. Grid markings in (a) and (b) are 1° in latitude and longitude (the latter being about 105 km in length), and both figures are $8^\circ \times 8^\circ$. (c) Bathymetry for the Niuatahi volcano (formerly named “Volcano O”) in the NE Lau basin near Tonga on Earth [14]. Scalebar is 2 km in length and depth colorbar ranges from -2700 m to -1100 m. (d) Magellan SAR image of Tepev Mons overlain on Magellan altimetry.

Where we stand: the Mars Analogy. The status of Venus geoscience is arguably at a level similar to that for Mars just prior to the arrival of the Mars Global Surveyor (MGS) spacecraft. At that time, the state of the art was reflected in imaging data from NASA’s Mariner and Viking missions, with typical resolutions of hundreds of meters per pixel for the latter [e.g., 15]. Topography was compiled from a hodgepodge of sources including Earth-based radar and satellite-based data including occultations and pressure readings from spectrometers [e.g., 16]; the resulting horizontal resolution was of order 10s of kilometers at best. MGS returned high-resolution imaging (Mars Orbital Camera, or MOC [17]) and topographic (Mars Orbiter Laser Altimeter, or MOLA [18]) datasets that revolutionized our understanding of the geologic, tectonic, and volcanic evolution of Mars (for geophysical examples see [19]). MOLA had ~ 350 m along-track spacing and across-track spacing that could be as good as several km or less near the equator, and much better at the poles. The pre-MGS Mars analogy is not exact: Magellan benefited from a dedicated radar altimeter, although the combination of large surface radar

footprint and wide orbit spacing [20] yielded gridded products with horizontal resolution on the order 10 km. Further, processing of Magellan stereo imaging [21] allowed creation of local elevation models with horizontal resolutions of 1-2 km (while maintaining the Magellan vertical resolution of order 100 m), but with limited coverage ($< 20\%$ of the Venusian surface).

Lessons from Mars: Enabling Breakthroughs. The data from NASA’s Viking Orbiter missions and contemporary supporting instruments on Earth and at Mars provided what was in essence a reconnaissance-level exploration, from which many first-order findings that provided a foundation for Mars science were gleaned. However, true revolutions in our understanding of Mars were made possible by the high-resolution datasets of MGS: from the MOLA topography, these include characterization of the hemispheric crustal dichotomy [22], inference of the Borealis Basin [23], and detection of the populations of buried impact basins in both the northern lowlands and southern highlands (the “Quasi-Circular Depressions, or QCDs, of [24]). These truly revolutionary insights of the post-MGS era for Mars were not possible until high-resolution datasets were available. A similar revolution awaits Venus, where volcanic systems can be fully characterized for the first time with high-resolution datasets.

Figure 2. Image and topography data from the TOPSAR airborne Synthetic Aperture Radar (SAR) for Fernandina, Galápagos Islands [25, 26]; the island is approximately 30 km across. Image data is overlain on topography; vertical exaggeration V.E. = 4:1 in both plots. (Top plot) Full resolution TOPSAR imaging overlain on topography (10-m postings). (Bottom plot) Imaging degraded to Magellan resolution (120 m/pixel) overlain on topography degraded to a 12 km by 5 km grid representative of Magellan across- and along-track resolution, respectively.

The need for improved resolution: a worked example. While the Magellan mission constituted a great leap in our understanding of the evolution of Venus, the resolution limits of the SAR imaging and radar altimetry datasets from that mission present an obstacle to progress in understanding Venus volcanism, even to the ability to identify first-order properties of volcanic systems. As an example, we consider an analogous terrestrial radar dataset, the TOPSAR airborne radar [25, 26] for the Fernandina volcano in the western Galápagos Islands chain. Fernandina is roughly 30 km in diameter and has the distinctive “inverted soup bowl” shape [27] characteristic of Galápagos volcanoes, with steep upper slopes at the rim of the

central caldera, transitioning to gentler lower flank slopes. These topographic features are also associated with the internal plumbing of the volcano [28, 29], with circumferential dikes creating grabens with those orientations on the steep upper slope, transitioning to radially oriented grabens/dikes downslope. These topographic-tectonic relationships are crucial clues to the internal workings of Fernandina and other Galápagos volcanoes, pointing out crucial magma pathways [28, 29] that are substantially different than those of “classic” shield volcanoes (e.g., Hawai‘i), and that point to influences of geophysical setting (including lithosphere thickness) in regulating magma ascent pathways [30].

In the full-resolution TOPSAR [25, 26] dataset (Fig. 2, top), Fernandina’s characteristic topographic zones can be seen quite clearly: central caldera, steep upper flanks, and shallow lower flanks. However, when the topographic data are degraded/averaged to Magellan resolution across and along track (Fig. 2, bottom), these features are no longer distinguishable, and the edifice resembles a typical broad shield profile. In particular, the steepening of the upper flanks occurs over a distance shorter than the spacing of Magellan’s orbital tracks and footprints, resulting in the smoothing out and removal of the critical central steep slopes. Note there are only a handful of topographic measurements in the degraded-topo image! Clearly, we are not sensing valuable information at Magellan resolution, and lacking such information we could not draw the correct conclusions regarding the distinct plumbing system of Fernandina [28, 29].

Improving data resolution enables breakthroughs. In the more than 30 years since the launch of the Magellan spacecraft, enormous leaps have been made in the technology and design of spaceborne Synthetic Aperture Radar (SAR) instruments. Such instruments can provide the greatly increased resolution required to fully characterize volcanic systems on Venus of the types described above. For example, missions to Venus have been designed around the capabilities of modern SAR instruments [for example, 31] that offer topography horizontal resolutions of order hundreds of meters/pixel (and vertical precisions on the order of meters). This would enable volcanology studies that were formerly limited to regions with stereo coverage to be carried out over the whole planet. Examples include: **1)** Lithospheric flexural studies of short-wavelength flexural topographic moats for coronae [32] and small volcanoes [4], establishing the presence or absence of moats planetwide, extending range of detectable elastic lithosphere thickness T_e to lower values, and greatly expanding the number of volcanic features that can be tested, allowing inferences of lithospheric strength and interior heat flux to be made over a much greater fraction of the surface of Venus. **2)** Topography-to-strain analysis of fracturing and intrusion at magmatic centers [33]. Topography can be used to evaluate strain on fault systems, which in turn can be used to constrain quantitative models of volcanic processes such as flexural loading (see previous example) and magma chamber inflation (a key to inferring magma plumbing pathways) [e.g., 33, 34]. **3)** Relations of volcanism to global-scale resurfacing and thermal evolution: this includes recognition of buried structures that can only be resolved by high-resolution topography, such as the QCD basins of Mars [24], and also rigorously characterizing contributions of volcanic edifices to plains unit volumes [2] (adding high-resolution imaging).

Moving on to the high-resolution “MGS Phase” of Venus studies would enable the shapes of fundamental volcanic structures like calderae to finally be resolved. Note the “plastered over” appearance of the Tepev Mons summit calderae (Fig 1f), as if that volcano were a work of art (and it IS!) poster-pasted onto a lumpy wall. This is exactly the same impression that the TOPSAR degraded-to-Magellan topography gives for the Fernandina volcano (Fig 2b). The topographic expression of the Tepev Mons calderae or neighboring pits and valleys are not represented in the coarse Magellan altimetry dataset. Finally being able to resolve these

structures, and dozens of others like them on Venus, would enable major advances in Venus volcanology. Further, improved datasets would facilitate studies of volcanoes with annular topography/tectonics, providing a more rigorous basis for classifications of “corona” vs. “caldera”. A sometimes unstated assumption in assigning a “corona” designation is that the feature in question is not obviously a caldera: i.e., there is no convincing evidence of central subsidence from magma withdrawal [see 2, 5]. Well, that distinction is not always so obvious: Niuatahi volcano (Fig. 1e) is a dead ringer for a Venus corona in topography/morphology, but is emphatically identified as a “caldera” in the cruise report [14]. Improved datasets can finally resolve such issues.

New momentum for planetary volcano studies. Facilitating the study of volcanoes on Venus by sending missions with modern radar instruments capable of collecting high-resolution imaging and topography datasets would drive progress in planetary science along several axes:

1) Understanding the planet Venus itself. Studies of volcanism on Venus address goals and objectives identified in the most recent “Venus Goals, Objectives, and Investigations” document [35] compiled by the NASA-chartered Venus Exploration Analysis Group (VEXAG). The most obvious connection is to Goal #3 “Understand the geologic history preserved on the surface of Venus and the present-day couplings between the surface and atmosphere.”, with the underlying objectives A) What processes have shaped the surface of Venus?, and B) How do the atmosphere and surface of Venus interact?”. These objectives are linked to seven Investigations, most of which apply directly to volcanological studies, including characterizations of the Geologic History, Geochemistry, Geologic Activity, and Crust of Venus related to Objective A of Goal 3. Volcanism also provides material input to the atmosphere of Venus through outgassing, thereby directly influencing surface/atmosphere interactions (Goal 3 Objective B), but also directly addressing the “Outgassing” Investigation of Objective B of Goal 2, “Understand atmospheric dynamics and composition on Venus”.

2) Accomplishing broader NASA strategic goals. NASA recognizes the value of “comparative planetology” in unraveling the evolution of planetary processes, and this approach has yielded consistent progress in volcanology. Advances in Venus volcanology inform the broader search to understand the geological and thermal evolution of planets, most specifically the rocky bodies of the inner solar system. Basaltic volcanism in particular has similar manifestations on Mars, such as tall and broad volcanic shield volcanoes and plains-covering flows (many with characteristic compressional ridges). In contrast, the smaller bodies Moon and Mercury generally lack the spectacular central edifices of the former two bodies (but see [36]), and are characterized by flows filling impact basins or broadly covering regions in the case of Mercury. In this scheme, Venus plays the role of the Earth-sized planet that lacks a global tectonic system, thereby creating individual affinities to various planets’ volcanic expressions that can be exploited to unravel the evolution of volcanism in the Solar System, and also pave the way to predictions of how extrasolar planets evolve volcanically.

3) Understanding Earth as a Planet! In the ultimate planetary feedback, improved characterization and understanding of volcanism on Venus drives a better understanding of Earth’s volcanic record! This perspective is vital, because Earth Science has historically been the foundation for modern “Planetary Science” as we know it (that is, scientific studies of planets not performed solely via telescope). “Closing the circle” here will enable the next generations of planetary scientists and earth scientists (may there be no distinction someday!) to unravel the fundamentals of planetary volcanism hand-in-hand!

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