"Planetary Volcanology: Progress, Problems and Opportunities".

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Abstract: Young on the scene, the field of planetary volcanology has transitioned from a predominantly descriptive science to a quantitative holistic view of the integrated generation, ascent and eruption of magma under very different planetary sizes, densities, atmospheres and positions in the Solar System. These multiple settings and conditions, now augmented by thousands of exoplanets, are providing new insights into the nature and history of volcanic processes and the thermal evolution of our own Home Planet, Earth.

Planetary volcanologists are like 'crime-scene investigators'
With very few exceptions (Io, Enceladus) we need to infer volcanic eruption processes that have occurred hundreds of millions to billions of years ago using only geomorphology (to infer edifice shapes and eruption styles) and remote sensing data (to infer surface properties and mineralogy). The conditions we take as given on Earth (gravity, atmospheric properties, surface temperature) vary extremely widely between other bodies (Figure 1). And many of the things we can determine readily on Earth (e.g., detailed magma composition and mineralogy, small-scale topography, gas composition) are mostly unknown elsewhere.

Undaunted by these facts, planetary volcanologists view the Solar System as an incredible laboratory for the study of the issues involved in the generation, ascent and eruption of magma

(Figure 1). The planetary geologic record can increase our understanding of volcanology by expanding the spectrum of eruption conditions unknown on Earth. What happens when an eruption occurs in a vacuum (the Moon), or at ~100 times Earth's atmospheric pressure (Venus)? What is the internal heat source for the huge eruption plumes on Io? How and why does magma reach the surface on one-plate planets (globally continuous lithospheres) characterized by crusts of lower density than the mantle and global in extent (Moon, Mars, Mercury, Venus)? What magma compositions, effusion rates and surface conditions are required to build and sustain an atmosphere from internal sources (Mars, Venus, Earth)? Can an atmosphere ever evolve to sufficient pressure to inhibit the further release of gas to the atmosphere from eruptions (Venus)? What is the effect of mantle oxygen fugacity on magma generation and composition (Mercury)? How does the scale and planform of mantle convection and volcanism vary over billions of years (Mars, Mercury, Moon)? What do the surface deposits of well-preserved, mantle plume-generated Large Igneous Provinces (LIPs) look like (Venus)? What can the geologic record of planetary volcanism tell us about the thermal evolution of planets (Moon, Mercury, Mars, Venus, and by inference, Earth)? How can progress on these questions help astronomers understand the nature of the emerging cornucopia of exoplanets?

To address these questions, planetary volcanologists engage colleagues from a wide variety of disciplines (geodesists, geophysicists, petrologists, geochemists, geologists, atmospheric scientists, astronomers, etc.) and employ multiple scientific approaches (e.g., observation, field studies, modeling, experiment, theory). We briefly highlight recent progress and future challenges on many of the above questions. We specifically summarize recent developments in planetary volcanology relating to the generation, ascent and eruption of magma in different planetary environments and how this leads to a better understanding of planetary volcanologic records and the general nature of planetary magmatic processes during thermal evolution. Additional perspectives can be gained from a) terrestrial field studies of analogues to planetary features (particularly related to rheology and flow emplacement), b) remote sensing studies that examine surface properties and composition (and in the case of the Moon the link to returned samples), c) geologic mapping studies that constrain ages, and d) (in the case of Mars), implications for volcanism from petrologic analyses of SNC meteorites (see Sigurdsson et al. 2015)

The Moon

Prior to the 1980's, lunar volcanism studies were largely descriptive, assisted by knowledge of the Apollo returned samples (Head 1976; Taylor 1975). Subsequently, the available data were synthesized to guide a theoretical model of the ascent and eruption of magma under lunar conditions (Wilson and Head 1981). Increasingly high-resolution images and altimetry of the Moon from Lunar Reconnaissance Orbiter (LRO), Chandrayaan-1 and the Chang'e missions have provided the means to refine (Wilson and Head 2017) and test (Head and Wilson 2017) models of the eruption conditions (Figure 2) that created the observed morphologies of lava flows, sinuous rilles and pyroclastic deposits. Unexpected volcanic features (Figure 2) have also been revealed - Irregular Mare Patches (IMPs) and Ring-Moat Dome Structures (RMDSs). Controversy surrounds their ages and modes of origin (Qiao et al. 2021; Zhang et al. 2020), but inflation and second boiling during lava flow emplacement may be important, as seen in flood basalt eruptions on Earth, and are likely to be a common feature in large-volume eruptions on all silicate bodies. Key locations where in situ measurements or sample return would clarify current thinking include RMDSs, IMPs and pit craters (skylights). Increased understanding of the patterns, abundances and rates of volatile release during lunar mare basalt eruptions provides testable predictions for the characteristics of pyroclasts in the Apollo sample collection and for future exploration goals on the Moon. Recent studies (Needham and Kring 2017; Head et al. 2021) assess whether mare basalt magmatic volatile release is sufficient to create a transient atmosphere for tens of millions of years, facilitating volatile transport to polar cold traps. Recently returned samples from the Procellarum-KREEP terrain will cast light on the role of elevated crustal radioactivity in mare basalt generation and eruption (Qian et al. 2021). In the coming decades, increased focus on robotic and human lunar exploration (Weber 2021) means that the Moon will serve as the cornerstone reference point for planetary volcanological studies.

Mars

The magnitude of the Tharsis region and its superposed huge shield volcanoes discovered by Mariner 9 in 1971 (Figure 3) has perplexed volcanologists for decades (Carr and Head 2010): How does the martian mantle supply magma for the billions of years of its construction (Solomon and Head 1982b), how do volcanic styles vary over this period, and how does the volcanic plumbing respond to these immense loads (McGovern and Solomon 1993). Detailed geological mapping in the ensuing decades (Tanaka et al. 2014a, b), development of a theoretical interpretive framework (Wilson and Head 1994), much higher resolution imaging and topography, and mineralogical data (Bibring et al. 2005) have improved our knowledge of eruption conditions and magmatic history (Zimbelman et al. 2020; Mouginis-Mark et al. 2021; Broz et al. 2021). Documentation of volcanic resurfacing of ~30% of Mars in the Early Hesperian by effusive and explosive eruptions (Head et al. 2002), the production of extensive pyroclastic deposits (Kerber et al. 2013), and the presence of extensive sedimentary sulfate deposits (Bibring et al. 2005) have raised questions about the role of changing atmospheric pressure, and its influence on magmatic gas release into the atmosphere (Gaillard and Scaillet 2014**)** as a function of time and altitude as the atmosphere thinned and Tharsis and its huge shields were built (Head et al. 2021a). At present, emphasis is focused on surface exploration and sophisticated analyses of sedimentary deposits in ancient lakes and oceans, but in the coming decades, attention will be focused on sample return, which should supply critical information about magmatic petrology and chronology. In the meantime, much attention will be focused on the nature of the Noachian atmosphere and climate, and the role of volcanism in determining atmospheric history and evolution to the present. For example, an increased understanding of magmatic gas release as a function of changing atmospheric pressure (with both elevation and time) is leading to an improved understanding of the role of pyroclastic eruptions and the contribution to atmospheric evolution and regional deposits, such as sulfates (Figure 2). The role of pyroclastic eruptions with time (Scott and Tanaka 1982; Mouginis-Mark et al. 1992; Crown and Greeley 1993) and changing ratios of effusive to explosive eruptions are critical to understanding martian volcanism and climate change. Wide-ranging spin-axis obliquity variations have led to mobilization of polar ice and transport to lower latitudes (including Tharsis) over the course of Mars' history, making Mars the Solar System laboratory for the study of volcano-ice interactions (Smellie and Edwards 2016). Indeed, one Noachian atmosphere model predicts “cold and icy highlands” (Figure 2), and it has been hypothesized that volcanic activity may have melted the ice sheet to produce the valley networks and associated lakes (Head and Marchant 2014). The coming decades of observation, theory and laboratory studies promise to reveal the critical role of volcanism in atmospheric origin and climate evolution, in interpreting the evolving hydrosphere and cryosphere, and in understanding the thermal and magmatic evolution of Mars (Baratoux et al. 2013; Grott et al. 2013).

Mercury

An understanding of the role of volcanism in shaping Mercury’s surface was inhibited for decades by the Mariner 10 mission finding that smooth plains were closely associated with the large Caloris impact basin and thus, like the Apollo 16 smooth plains (Oberbeck et al. 1975), might be of impact, not volcanic origin (Vilas et al. 1988). Furthermore, Mercury’s high density and solar proximity led to predictions of volatile depletion and lack of explosive volcanic activity. The MESSENGER mission (2011-2015) provided baseline data on the surface chemistry and geology, confirming a volcanic origin for the smooth plains, and also revealed abundant examples of pyroclastic activity (Solomon et al. 2018). Missing from the volcanic record, however, were shield volcanoes and other distinctive landforms and deposits seen on the Moon. This, and evidence that the plains were emplaced over a geologically short time interval compared with the Moon, could be testimony to the large core and correspondingly thin mantle influencing convection scale-lengths and patterns, perhaps favoring flood-basalt volcanism (Wilson and Head 2008). Unknown too is the chemical nature of the mantle and its oxygen fugacity, critical to magma generation (Zolotov et al. 2013). Ice deposits in permanently-shadowed polar craters may provide clues to magmatic volatiles, but could also be derived from cometary impacts (Deutsch et al. 2021). The upcoming BepiColombo mission (Benkhoff et al. 2010) will measure the elemental and mineralogical composition of the surface at higher spatial resolution for a much wider range of elements and compounds. Needed is a framework of theoretical treatments of the ascent and eruption of magmas linked to the nature and chemistry of Mercury’s mantle, the evolving lithospheric state of stress, and Mercury’s thermal evolution.

Venus

Is Venus the most Earth-like terrestrial planet (similar in size, density and position in the Solar System) (Figure 4), with plate tectonics focusing its volcanism at plate boundaries, or is it like the smaller bodies, a one-plate planet losing heat by conduction and via hot-spot mantle plumes? With its thick, opaque atmosphere (Figure 4), Venus has been slow to reveal its volcanological record. Clearly, the current runaway greenhouse conditions (CO_2 dominant, some sulfur species, ~93 bars atmospheric pressure, surface temperatures of ~740 K), all point to a significant role for volcanism in its atmospheric and surface evolution, possibly even today (Bougher et al. 1997). Early radar data and landers gave hints of volcanism (Hunten et al. 1983), but a regional and global picture of the surface were not forthcoming until the Venera 15/16 (1983-1985; Basilevsky et al. 1992) and Magellan (1990-1994; Saunders et al. 1992) missions. Global radar mapping and topography revealed 1) that ~80% of the surface is of volcanic origin

(Figure 4), 2) that the globally distributed regional plains were likely to have been emplaced in a geologically short period of time, and 3) that the exposed geological record represented only the last <20% of Venus' history, showing no evidence for current plate tectonics. Theoretical analyses showed that the extreme current atmospheric temperature and pressure could enhance lava flow rates, inhibit explosive volcanism, and significantly affect the volatiles that were released into the atmosphere (Head and Wilson 1986), and even influence magma reservoir depths and behavior as a function of altitude (Head and Wilson 1992). Current Venus research faces three conundra:

1) What global geodynamic forward-models of the first 80% of Venus' history can best explain the currently observed geological record?

2) When did the current atmosphere form and evolve to its current state? How can inverse models, using the observed geologic record, inform us as to whether Venus might have had an Earth-like climate until relatively recently, even into the last 20% of its history (Way and Del Genio 2020). Could one or more Large Igneous Province (LIP)-like massive fluxes (Ernst 2014) cause such a transition? Recent estimates of volcanic deposit volumes and fluxes from the observed geologic record suggest that the current atmosphere was not derived from volcanism in the last 500-1000 Ma, but rather is more likely to be a 'fossil' atmosphere dating from earlier Venus history (Head et al. 2021), but more detailed geologic mapping, much higher resolution topography, gravity and image data, and new data on the isotopic composition of the Venus atmosphere are needed.

3) Does the presence of steep-sided viscous domes and festoons mean that Venus has undergone sufficient petrogenetic differentiation to produce more silicic rocks (granites, rhyolites) or could these be explained by atmospheric pressure-induced bubble-rich high viscosities in basaltic magmas (Pavri et al. 1992; Stofan et al. 2000)?

Fortunately, by the end of the decade, NASA will send both an orbiter (VERITAS) and probe (DAVINCI+), ESA an orbiter (EnVision), and Russia an orbiter, probe and lander (Venera D) to address these three conundra. Furthermore, recent hints that the planet may currently be (intermittently) volcanically active (e.g., Smrekar et al. 2010; Shalygin et al. 2015; D'Incecco et al. 2017; Gulcher et al. 2020; Filiberto et al. 2020) underlines the need for these missions to obtain atmospheric data, high-resolution infra-red measurements, and improved image, reflectivity and topography data. In addition, targeted in situ analyses of surface rocks on flood lavas, viscous domes, coronae and tesserae would enormously increase our understanding of Venus' geologic and volcanological history.

The Galilean Satellite Io

The abundant and continuous volcanic eruptions on Io make it the key laboratory for study of effusive and explosive eruption processes in a vacuum on a lunar-sized body (Davies 2007). Synthesis of visible images and infrared data from Galileo with ongoing Earth-based infrared observations, coupled with models of high-volume-flux eruptions, allows estimates of the volumes of magma and volume eruption rates in a range of explosive and effusive eruption types. Models of explosive eruptions developed to understand pyroclast dispersal on the Moon (Morgan et al. 2021) are also applicable to the "plumes", better regarded as fire-fountains, on Io. A future dedicated Io volcano observation/monitoring mission would greatly enhance this knowledge.

Expanding Volcanological Horizons
Recent and planned Solar System exploration is significantly expanding our volcanological horizons by offering key insights into the origin and evolution of comets, asteroids, icy satellites and Kuiper-belt objects (KBOs). Can explosive volcanism occur on a small asteroid? Do cometary jets qualify as explosive volcanism? How does recent cryo-volcanism operate on tiny icy satellites such as Enceladus? How do ammonia, water, and even nitrogen volcanism operate in the extremely low temperatures of the outer Solar System and the Kuiper belt (Kargel et al. 1991; Neveu et al. 2015)?

Home Planet Earth
As revealed elsewhere in this issue, significant advances have been made in all aspects of terrestrial volcanology, yet our global view is dominated by current activity and activity at divergent and convergent plate boundaries, and hot-spot volcanism. We have never observed the emplacement of a Large Igneous Province, nor do we know when plate tectonics started, how it varied with time, and indeed what came before (Rollinson 2007). Volcanological exploration of the Solar System provides important insight into the missing chapters of Earth history, and indeed helps us clarify and refine our current Earth volcanological paradigms.

The 'final' frontier is the role that volcanism plays in the formation and evolution of exoplanet surfaces and atmospheres! Discovery of dozens of Venus-like exoplanets (Kane et al. 2019), for example, provides a larger population and parameter space to explore and understand the limited examples in our Solar System, including Earth!

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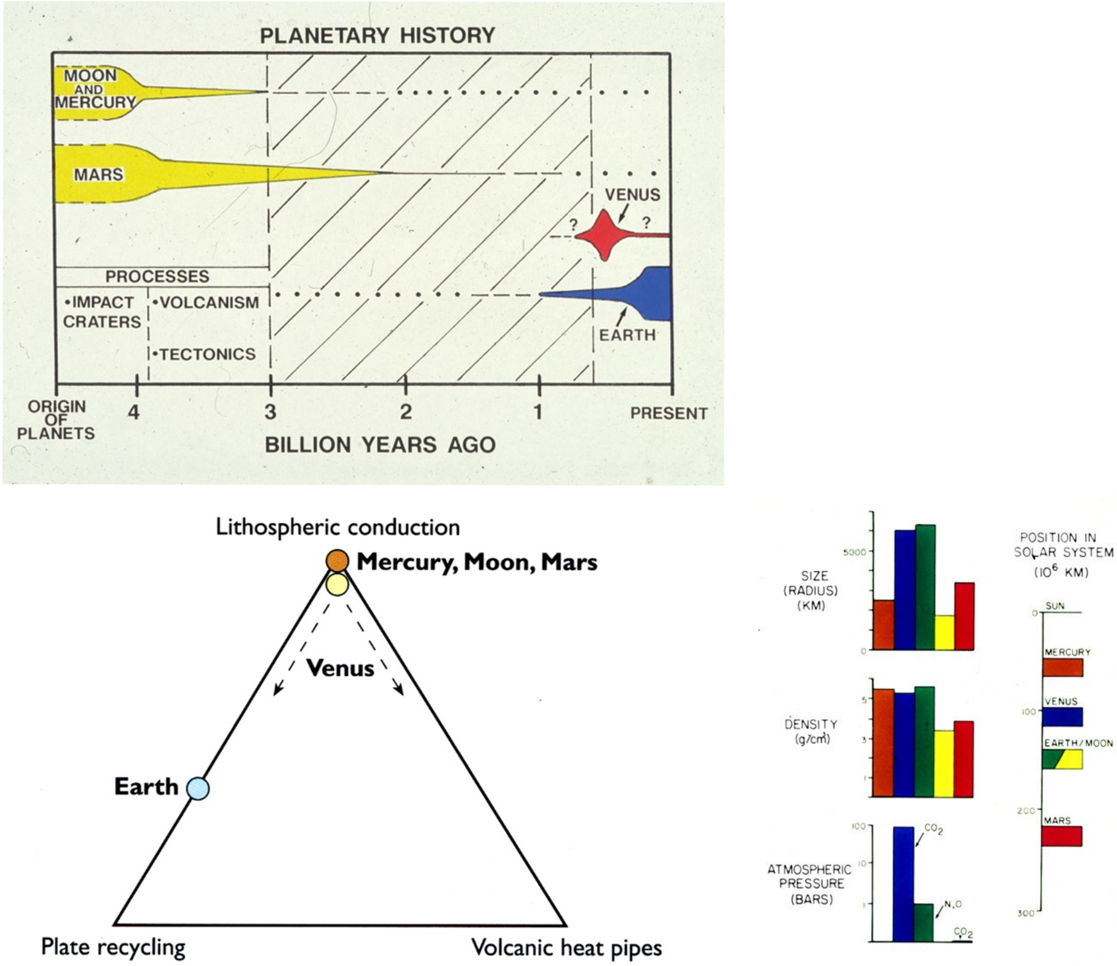
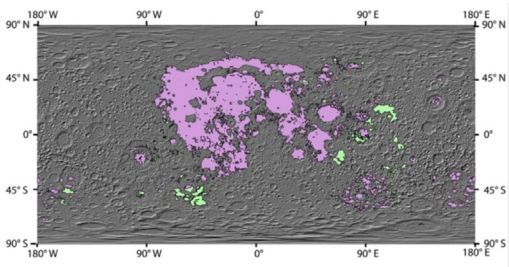
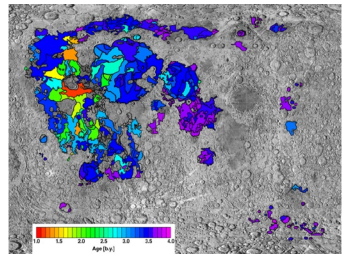
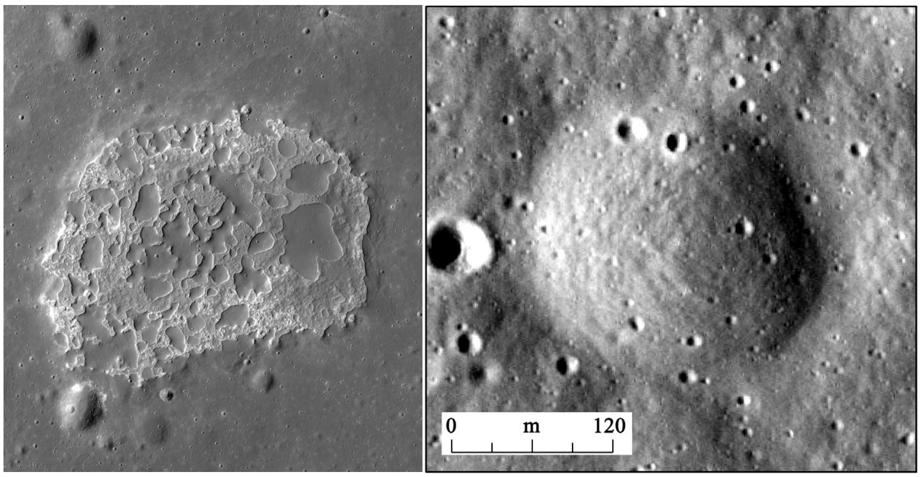


Figure 1. The Planetary Geological Record: (a) Geological record currently preserved on the terrestrial planetary bodies dating from different periods in their history. Height of each bar represents the approximate percentage with time (for example, ~60% of Earth's surface is ocean floor formed in the last ~200 Ma). Volcanism has been hypothesized to continue to the present on Mars (dashed-dotted line). Impact cratering dominated the early history of all of these bodies, giving way to volcanism and tectonism. (b) The end-member lithospheric heat loss mechanisms (conduction, plate recycling, radioactive decay of surface rocks, and advective heat pipe, as demonstrated by Io, the innermost of the Galilean satellites of Jupiter). (c) Terrestrial planetary body variations in size density, position in the solar system and composition/surface pressure of the atmosphere. Modified from Head (2002) and Solomon and Head (1982a).







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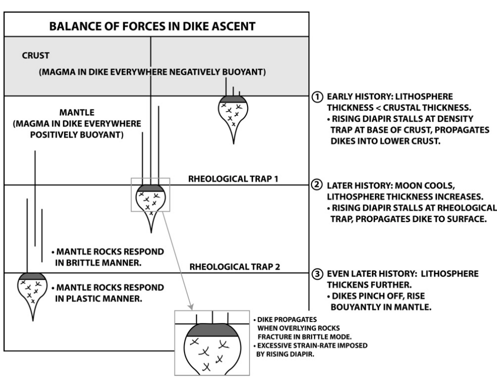

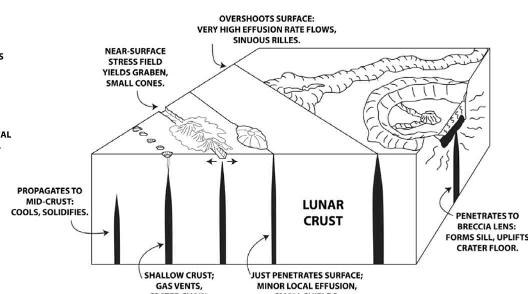

(e)

Figure 2. Volcanism on the Moon: The geological record of basaltic volcanism on the Moon. (a) Distribution of mare basalts (purple) and cryptomaria (green). (b) The ages of mare basalts on the basis of impact crater size-frequency distributions chronology tied to returned sample data points (after Hiesinger et al. 2011). (c) Examples of an Irregular Mare Patch (IMPs) (Ina; 2 x 3 km) (top) (Braden et al. 2014), and Ring Moat Dome Structures (RMDS) (bottom) (Zhang et al. 2020) thought by many to have formed in the last 100 Ma (less than the last 2%) of lunar history (see review In Qiao et al. 2021) (d) Basic principles and factors in lunar magma generation, ascent and eruption (from Wilson and Head 2017). (e) Dike emplacement in the upper part of the lunar crust and implications for intrusion and eruption (from Head and Wilson 2017).

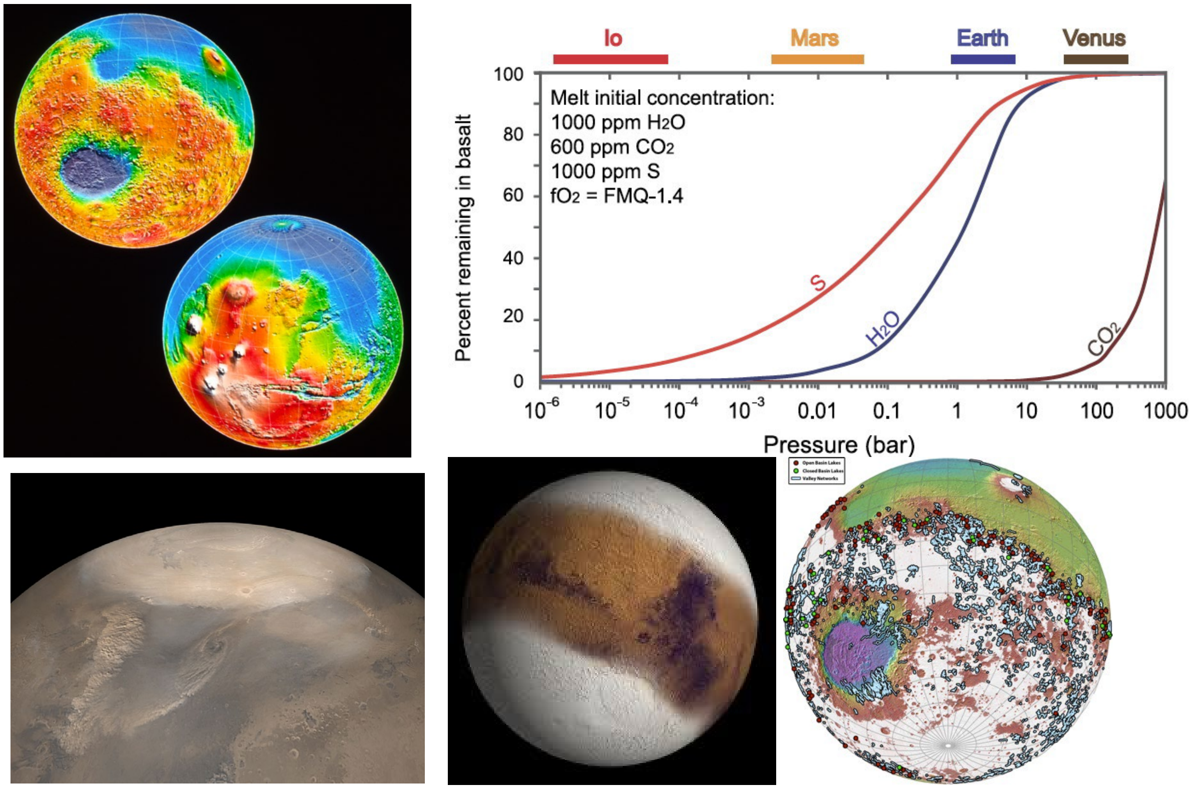

Figure 3. Volcanism on Mars: Topographic map of Mars (a) showing the Tharsis rise (5000 km wide and rising ~7 km above mean planetary radius) with superposed Tharsis Montes and Olympus Mons volcanoes, each rising over 10 km above their base elevations. The smaller Elysium volcanic rise is seen at top right). (b) Volatile release as a function of changes in atmospheric pressure on Mars showing the effects of changes in atmospheric pressure in altitude and time on explosive volcanism and release of different gas species into the atmosphere (Gaillard and Scaillet 2014**)**. (c) Significant obliquity variations on Mars mobilize polar ice (top) and redistribute it to lower latitudes (middle), and as low as the tropics, ensuring that volcanic eruptions and glacial ice interactions have occurred throughout the history of Mars. One model for early Mars history suggests that the highlands were cold and icy (bottom) and might have been the source of water for valley networks, and martian lakes (Head and Marchant 2014).

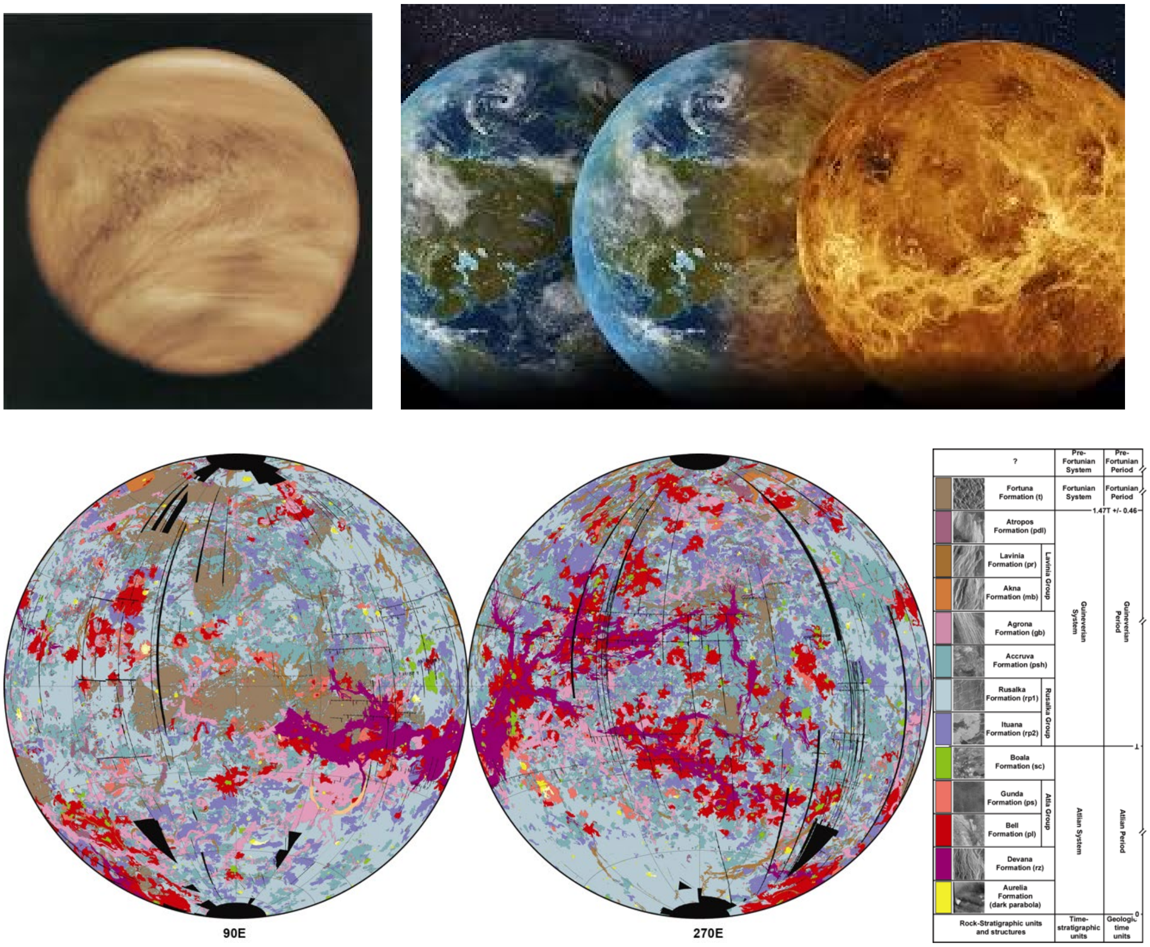

Figure 4. Volcanism on Venus: Volcanism and the origin of Venus' atmosphere. The Venus atmosphere (top left) is currently characterized by ~93 bar atmosphere pressure, significantly inhibiting gas exsolution and explosive eruptions (see Figure 3b). Venus' atmosphere may have once been Earth-like, transitioning to its current state geologically recently (top right). Could the extensive (80% of the surface) volcanic resurfacing recorded in the last <1 Ga have produced the current atmosphere transition from an earlier Earth-like atmosphere? The global geological record (bottom left, geologic map, and bottom right, stratigraphic column; Ivanov and Head, 2011; 2013; 2015) can be used to test this hypothesis.