The Importance of Planetary Volcanism and Key Investigations for the Next Decade

Advancing our Understanding of Planetary Interiors, Surfaces, Atmospheres, and Habitability

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Lead Author: Laura Kerber

Jet Propulsion Laboratory / California Institute of Technology
Oak Grove Dr. Pasadena, CA 91001.
Email: kerber@jpl.nasa.gov
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Co-Authors:

Paul K. Byrne (North Carolina State)
Ashley Gerard Davies (JPL/Caltech)
Christopher W. Hamilton (U. of Arizona)
Devanshu Jha (MVJ College of Engineering)
James T. Keane (JPL/Caltech)
Laszlo Keszthelyi (USGS)
Rosaly M.C. Lopes (JPL/Caltech)
Heather Meyer (JHU APL)
James Head (Brown University)
Catherine Elder (JPL/Caltech)

Co-Signatories:

The paper has 111 co-signatories, listed with their affiliations on this page:
Briony Horgan, Lisa Gaddis, Timothy Glotch, David A. Williams, Clive R. Neal, Lionel Wilson, Brett Denevi, Samuel Lawrence, Alfred McEwen, Stephen Elardo, Rachel Klima, Richard Palin, Debra Needham, Vincent F Chevrier, Ross A. Beyer, Kim Cone, Juliane Gross, Jennifer Whitten, Shashwat Shukla, Brian Day, Joseph M. Boyce, Junichi Haruyama, Sarah A. Fagents, Zhiyong XIAO, Sarah Horst, Walter S. Kiefer, Benjamin J. Hockman, Kerri Donaldson Hanna, Farid Salama, Kelsi Singer, Ariel N. Deutsch, J.R. Skok, Sukrit Ranjan, Kate Craft, Youxue Zhang, Roberto Bugiolacchi, Stuart J. Robbins, Yuqi Qian, Andrew J. Ryan, Katherine de Kleer, Sarah S. Sutton, Brendan A. Anzures, David T. Flannery, M. Elise Rumpf, Aditya Khuller, Colin Jackson, Rina Noguchi, Tanguy Bertrand, Donald Hooper, Hannes Bernhardt, Sriram Bhiravarasu, Christian Klimczak, Kyle Uckert, Neeraj Srivastava, Tim Lichtenberg, Stephen Kane, Donald C. Barker, Jennifer G. Blank, Christopher Tylor, Katherine Shirley, Marissa Lo, Catherine Walker, Gerald Patterson, Justin I. Simon, James Haber, Vidhya Ganesh Rangarajan, Benjamin Greenhagen, Michael Torcivia, Indhu Varatharajan, Cesare Grava, Erika Rader, Georgiana Kramer, Catherine Corrigan, Joshua T.S. Cahill, Daniel Moriarty, Frances Rivera-Hernández, Jose M. Hurtado, Jr., Kristen Bennett, James W. Ashley, Nicholas Schmerr, Christopher Yahnker, Patrick McGarey, Amy McAdam, Jani Radebaugh, Laura Fackrell, Rosalind Armytage, Daniel C. Berman, Corbin Kling, Tabb C. Prissel, Jacob Richardson, Amy J. V. Riches, Lauren M. Jozwiak, Marie J.B. Henderson, Caitlin Ahrens, Alice Lucchetti, Maurizio Pajola, R. Glenn Sellar, Sona Hosseini, Carolyn Parcheta, Heather D. Smith, Amber L. Gullikson, Lynnae C. Quick, Anne Pommier, Thomas Giguere, William Rapin, Jessica Flahaut, M. Alexandra Matiella Novak, Aaron Curtis, Divya M. Persaud, Melissa Roth, Vince Roux.

Executive Summary: The study of volcanism is critical for understanding planetary structure and evolution in our Solar System and beyond. Volcanic processes contribute to planetary heat loss, reveal interior compositions and physical crustal structure, form and replenish atmospheres, and support life. Priorities in the next decade include observing heat flow processes on various planetary bodies, sampling a diversity of lava compositions (especially from bedrock outcrops and lava sequences), tracing volcanic volatiles from source to sink, connecting measurable lava morphological features with lava processes, characterizing the duration and magnitude of planetary lava emplacement events, improving estimations of instantaneous lava and gas fluxes for use in climate models, and understanding the pathways by which volcanism enables and supports life.

1. Introduction

Volcanism is a fundamental geologic process that shapes the evolution of the solid bodies of the Solar System. The realm of volcanism stretches from the interiors of planets, across wide swaths of their surfaces, and into their atmospheres and exospheres. Volcanism plays a principal role in planetary histories—from heat loss following accretion to the creation and maintenance of habitable environments. The study of volcanic deposits provides insight into these processes even long after they have ceased. This white paper summarizes the importance of volcanism as a planetary process both in the Solar System and beyond (Section 2) and outlines measurements that should be prioritized to address outstanding questions over the next decade (Section 3).

2. The Importance of Volcanism

A. Volcanism as a Mechanism of Heat Loss

The record of volcanic events preserved on a planetary surface provides a window into its history of heat loss—as the body cools, its ability to create melts diminishes, and volcanism declines (Solomon, 1978). By observing the total duration of activity, and secular trends of volcanism on multiple planetary bodies, we can unravel how a planet's size and composition relates to its heat production through time (see Byrne, 2019). In addition, volcanism plays an active role in cooling the planet by transferring hot material from its interior upwards into its crust and onto its surface (van Thienen et al., 2005). On some bodies, such as Io, this volcanic "heat pipe" advection is thought to dominate heat loss (Moore, 2001). By measuring the heat flow from planetary surfaces, modeling heat-loss processes, and observing different mechanisms of heat loss, we can understand the interplay between thermal evolution, volcanism, and tectonism throughout the history of the Solar System.

B. Volcanism as a Probe into Interior Composition

Volcanism is one of the principal ways we are able to understand planetary interiors, providing data complementary to geophysical methods such as seismology, geomagnetism, gravity, and geodesy. Since each volcanic unit represents a sample of the interior both in space and in time, volcanic deposits provide unique and essential constraints on the geochemical and petrologic evolution of planetary interiors. Compositional variations in volcanic deposits on the surface of a planet may reflect chemical heterogeneities between melt source regions, or could develop through partial melting or crustal assimilation as the magma travels from its source to its final solidification on the surface (e.g., Neal et al., 1994). Variations in source compositions can originate from vertical differentiation within a body, incomplete lateral mixing of a body's mantle, or depletion of the mantle source through time (Neal and Taylor, 1992). The composition and mineral assemblages found within volcanic products can reveal whether the interior was oxidizing or reducing (Haggerty, 1978). In these ways, measuring the compositional variety of surface volcanic deposits and determining their source depths and parent melt compositions provides critical information about the chemical composition and structure of the interior.

C. Volcanism as a Window into the Physical Properties of the Crust

To reach the surface, magma must travel from its source region up through the lithosphere. The density contrast between the rising magma and its surroundings (Solomon, 1975) and the prevailing tectonic regime in the lithosphere (compressional or extensional; e.g., Byrne, 2019), determines whether magma reaches the surface, where it can be stored in the crust, and what types of volcanic landforms it creates (Head and Wilson, 2017). As such, the combined study of the tectonic and volcanic history of a body can provide an in-depth view of the state and evolution of its lithosphere. Numerical models (Wilson and Head, 1981; 2017; Mastin, 2002) use rates of eruption, volatile contents, and composition (density) as key constraints to determine the magma's depth of origin and style of eruption.

D. Volcanism as a Creator of Planetary Surfaces

Volcanism is important for planetary surface science because it provides the "canvas" upon which the other geological processes take place. For example, tectonic models for wrinkle ridge formation on Mars must consider the strength of the basaltic lavas that are being deformed (e.g., Watters, 1991). Studies of the hydrological alteration of martian mudstones in Gale Crater must account for the mineral and elemental composition of their volcanic precursors (e.g., McClennan et al., 2014). The erodibility of basalt flows versus ash deposits affects the shape of martian river valleys (Gulick and Baker, 1990). Volcanic surface deposits (including lava and ash) cover up older geologic sequences and landforms, obscuring them from orbiting cameras, but potentially preserving them from degradation. For example, paleoregolith layers from early in Solar System history are likely preserved between lava flows on the Moon (Fagents et al., 2010). These layers may hold traces of ancient solar wind and galactic cosmic rays, acting as a time capsule for the early Sun (Crawford et al., 2008). On Mars, ash layers or lava flows could protect a record of ancient hydrological environments (Burr et al., 2009) and organic materials (Farmer and Des Marais,1999) from degradation. As they are well suited for radiometric dating, both ash horizons and lava layers act as bookmarks in the stratigraphic record, providing precise ages bracketing important events. On a longer timescale, volcanic plains provide wide, flat, units of a single age that are necessary for crater counting studies (Shahrzad et al., 2019), and volcanically filled and flooded landforms provide time markers for distinguishing between overlapping events.

E. Volcanism as a Creator of Atmospheres

After the primary, accretion-related atmosphere has dissipated, outgassing of endogenic volatiles is largely responsible for creating and maintaining the secondary atmospheres and volatile reservoirs of the terrestrial planets (Pollack and Yung, 1980; Gillmann et al., 2011), though the extent to which materials from comets or asteroids have contributed is debated (e.g., Morbidelli and Wood, 2015). The nature of the planet's interior (e.g., temperature, pressure, oxygen fugacity, etc.) affects the mass and composition of the resultant atmosphere. Whether an atmosphere forms at all is a function of the flux of gas released over time (e.g., Pollack and Yung, 1980; Needham and Kring, 2017) versus the rate at which it is stripped away from the planet (at the top) and incorporated into minerals (at the bottom). Volcanism also plays a role in this latter process by providing a source of fresh, unweathered bedrock, thus contributing to the drawdown of planetary atmospheres as well as their replenishment (Abbot et al., 2012).

F. Volcanism as a Creator and Destroyer of Habitable Environments

Volcanism provides sources of heat, nutrients, and chemical disequilibria, which were key for supporting early forms of life on Earth (Kelley et al., 2002). Serpentinization-driven hydrothermal vents are frequently invoked for origin-of-life scenarios, as they are thought to be rich in environmental disequilibria that could have been harnessed at the onset of metabolism (Barge et al. 2017). Similar environments could support life on ocean worlds (e.g., Hand et al., 2009).

Consistent levels of volcanic outgassing can help maintain a stable atmosphere over long periods of time, providing an environment that is favorable for life. If volcanic outgassing on a planetary body is not sufficient to balance atmospheric loss, an atmosphere may never form to protect life from harmful radiation, extreme temperature swings, and small meteorite impacts. On Earth, volcanism plays a key role in the climate-stabilizing feedback effect between outgassing, silicate weathering, and plate tectonic recycling (Foley et al., 2015). However, pulses of extreme volcanic outgassing can be extremely disruptive to life, as suggested by the strong correlation between flood volcanism and mass extinctions on Earth. The extent of that disruption is related to the volume of gas released and the duration of the event that released it, but many of the details on the mechanics of the extinctions are still under study (Bond and Grasby, 2017). Venus and Mars both have large igneous provinces that dwarf the largest known provinces on Earth. Catastrophic outgassing of CO_2 from several large events on Venus could have triggered its runaway greenhouse (Way and Del Genio, 2020). Depending on the duration of their emplacement events, these eruptions could have had catastrophic effects on the climates of their planets—including potentially extinguishing nascent life.

G. Volcanism as a Universal Planetary Process

In the last decade, numerous exoplanetary worlds have been discovered by telescopes such as TESS (Transiting Exoplanet Survey Satellite) and Kepler. Some of these planets are in orbits around their stars that could produce global magma oceans or high tidal stresses that may sustain considerable volcanism. New findings from exoplanets are important because they provide many additional “experiments” in the natural laboratory of planetary volcanism, each with a different set of conditions allowing models to be tested for a wide range of parameters.

3. Key Tasks for the Next Decade:

A. Heat Loss

Significant progress has been made on the theory and modeling of planetary heat loss, including links between body size, tectonic regimes, core formation, heat transfer mechanisms, and durations of volcanic activity (Breuer and Moore, 2015). Several activities are suggested for the next decade to validate and extend these models:

a. *Measure planetary heat flow and crustal thickness* (as InSight is currently doing at Mars; Smrekar et al., 2019) to provide critical constraints for volcanic models. Additional probes to the Moon, especially inside and outside the enhanced radioactivity of the Procellarum KREEP terrane (Joliff et al., 2000), would reveal the spatial variability of both heat flow and crustal thickness (e.g., Shearer and Tahu, 2010). Measuring Io's heat flow is critical to understanding the evolution of tidally-heated worlds (Keane et al., 2020).
b. *Confirm active or recent volcanism.* Recent observations suggest active volcanism on Venus, geologically recent outgassing on the Moon, and potentially volcanic methane outgassing on Mars. Confirmation of these results would affect our understanding of the timescales over which the planets cool.
c. *Further understand heat loss mechanisms.* Jupiter's moon Io is thought to lose most of its heat through "heat pipe" advection via volcanic conduits (Moore, 2001). In the past, the other terrestrial planets may have passed through a phase of heat loss dominated by this process (Moore et al., 2017), and additional observations of Io are needed to understand it. Modeling efforts are also needed to further compare advective heat loss planets with stagnant lid and plate-tectonic planets.

B. Interior Composition

The extent of our knowledge of the chemical structure of planetary interiors is uneven across the Solar System. On the Moon, returned samples and global remote-sensing datasets have provided enough information to form testable hypotheses for the interior structure of the Moon and its formation. On Mercury, foundational compositional information remains to be collected. Critical future activities include:

a. *Characterize a diversity of lava types,* including in-situ elemental chemistry or sampling of spectrally and chronologically diverse lavas and pyroclastic deposits on the Moon and Mars, compositional remote sensing (in-situ where possible) of deposits on Venus, Mercury, and Io, and compositional determination of exotic ices in the outer Solar System (e.g., Pluto).
b. *Investigate layered sequences of lavas*. Using float samples taken from planetary regolith for petrologic studies introduces uncertainty in their results due to a lack of known cooling history and difficulty in identifying samples of primary melts. In-place (autochthonous) igneous exposures and stratigraphies should be targeted to provide the most complete context for petrologic studies.

c. *Investigate evolved compositions.* The discovery of substantial volumes of evolved melts on planetary bodies such as the Moon (e.g., lunar domes), Mars, and possibly Venus (e.g., pancake domes and perhaps even the tesserae) would be paradigm-shifting for our understanding of recycling and partial melting processes that form and modify the crust.
d. *Determine the volatile content of planetary interiors.* Measurements and observations over the last decade have confirmed that both the Moon and Mercury had more volatile-rich interiors than previously thought (e.g., Saal et al., 2008; Kerber et al., 2009). Understanding the types and quantities of magmatic volatiles in rocky planetary bodies, determining how those volatiles exsolve under different conditions, and understanding their ultimate fates (e.g., incorporated into minerals, sequestered in cold traps, or lost to space) remains a high priority for the next decade.

C. Physical Properties of the Crust

Progress has been made on modeling the effects of density contrasts and stress regimes on the ascent and eruption of magma and their resultant volcanic landforms (e.g., Head and Wilson, 2017; Byrne, 2019). The Moon remains the most tractable case for understanding the underlying theory of magma ascent, as it has the advantage of a primary crust of known composition through which magmas ascended (Head and Wilson, 1992). Application of this theory to other planets is needed to test the implications of the models in different regimes. Priorities include:

a. *Infuse geologic constraints into planetary evolution models.* Geologic mapping results are approaching the point where constraints on timing and nature of both tectonism and volcanism can be incorporated into evolutionary models.
b. *Improve ascent modeling in icy crusts* and investigate whether tidally modulated stresses in conduits inhibit or bolster the eruption of cryolavas (see white paper by Walker et al., 2020).
c. *Determine intrusive-to-extrusive ratios of volcanic material in planetary crusts.* Intrusive materials can contribute to a densification of the crust over time, facilitate heat loss, and contribute otherwise unaccounted volcanic gases to the atmospheric system.
d. *Determine how crustal structures affect the style of volcanism* (low vs. high density crusts; one-plate crusts vs. tectonic plates), including the tendency for sustained or pulsed eruptions, and the physical controls on the distributions of eruptive activity.
e. *Understand near-surface eruption behavior,* including the solubility of volatile mixtures and the behavior of bubbles/foams under shear/flow.

D. Creation of Planetary Surfaces

Global imaging and expanded high-resolution topography (especially from the Moon and Mars) has increased available information on lava terrains and landforms. Important work remains to link remotely observable volcanic patterns to the processes that create them:
a. *Improve estimates of instantaneous and average lava fluxes* by linking them to measurable flow properties (e.g., via models verified with observations on Earth; Hamilton et al., 2020; Aufaristama et al., 2020)
b. *Improve flow volume estimates* by measuring flow thicknesses in-situ (Rumpf et al., 2020)

c. *Quantify fractions of volcanic products erupted on each planet by eruption style* (e.g., inflated lavas, compound flow fields, lava transported in tubes, turbulent channels, explosive deposits, etc.) Higher resolution radar images are needed to complete this work on Venus.
d. *Identify, map, and observe cryovolcanic features and processes*. Develop a clear set of diagnostic observables for classifying a feature as cryovolcanic. Map cryovolcanic features on icy bodies. Observe active cryovolcanic processes (Enceladus plumes, Triton geysers), and search for new examples (Europa, Ganymede, Titan, Ariel, Pluto).

E. Creation of Atmospheres

Work has been done to estimate the cumulative amounts of gas that have been released into planetary atmospheres over time (e.g., Craddock and Greeley, 2009). These studies yield average flux rates across millions of years, with gas contents usually based on terrestrial analogs. Increasingly sophisticated planetary climate models require flux estimates on a much shorter timescale (weeks to years). In the next decade, our understanding of the impact of volcanic eruptions on planetary atmospheres can by improved in several ways:

a. *Improve estimates of instantaneous and average gas fluxes* by linking measurable lava properties (vesicles, lava eruption types) with gas fluxes.
b. *Determine how the composition of planetary lavas and gases have changed over time.*
c. *Determine the impact of volcanic eruptions* on the climate/exospheres of Mars, Venus, Mercury, the Moon, and Io, and assess their contribution to the atmospheres of Titan and Pluto, the Jovian magnetosphere, and Triton's plasma environment.

F. Creation and Destruction of Habitable Environments

Over the last few years, a close relationship between volcanism and the origin and evolution of life on Earth has become better understood. Progress can be made in the following ways:

a. *Explore the role of macro- and microscale volcanic processes in the origin and evolution of life*, including in the creation of environments, the supply of nutrients and energy, and the support of ancient metabolic pathways.
b. *Establish the effect of major volcanic outgassing on extinctions* recorded in Earth history, and apply those lessons to planetary habitability more broadly via improved modeling.
c. *Determine the role (if any) of volcanic emissions from Io in the habitability of Europa.*

G. Volcanism on Exoplanets

In the coming decades, new telescopes will investigate the atmospheres of planets around other stars like never before. Transit and orbit observation techniques may enable characterization of select, plausibly volcanic exoplanets, and their chemistry (e.g., 55 Cnc e; Henning et al. 2018). A fundamental understanding of the theoretical range of volcanic outgassing and its effects on planetary atmospheres is needed to be able to interpret these new observations (e.g. Noack et al., 2017; Ramirez and Kaltenegger, 2017).

4. Conclusion

Major progress in our knowledge of planetary volcanism is possible in the next decade. Additional compositional and geophysical data is needed from Mercury (see white paper by Byrne et al., 2020), and improved radar and chemical data are needed for Venus. Exploration of the Moon and Mars should prioritize in-situ exploration with a diverse sampling strategy, especially of bedrock outcrops, lava sequences, pyroclastic deposits, and end-member volcanic features and units. Exploration of the outer Solar System should focus on capturing active processes to help interpret past features and provide constraints for theoretical models. A strong research and analysis program combining modeling, geologic interpretation, field work, and laboratory experiments is vital for synthesizing data returned from spacecraft missions.

5. References (Long Form of References)

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