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Volcanic Diversity throughout the Solar System

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1.1. INTRODUCTION: "A LITTLE AMBIANCE"

What comes to mind when one considers the subject of volcanism in the solar system? The ongoing eruptions on Io, the enormous shield volcanoes of Mars, the low-profile volcanoes of Venus, or the nitrogen-powered geysers of Triton are but a few of the dramatic examples of planetary volcanism discovered in recent years. Yet each of these examples occurs within a distinctive environment. We usually think of "environment" as merely the backdrop to main events that created the impressive volcanic features evident throughout the solar system. However, in this book we hope to demonstrate that the environment into which a volcanic eruption takes place is a significant—and perhaps even a controlling—factor on the resulting eruption styles and products. Much can be learned by comparing volcanic features observed in various locations throughout the solar system. The goal of the present compilation is to increase awareness of volcanic diversity on solid surfaces, paying special attention to the local planetary environment.

The book is organized to progress roughly from more accessible to less familiar subjects, with liberal cross-referencing to aid the reader in the comparison process. Volcanism in the solar system occurs on objects of varying sizes (Figure 1.1), and which encompass a range of basic physical conditions (Table 1.1). The order of discussion proceeds from subaerial volcanism on Earth (Chapter 2—the primary source of current information on volcanic processes), to extraterrestrial examples with similar—and increasingly different—ambient conditions. Chapter 3 compares the interaction of lava with water and ice on Earth and Mars. Mars (Chapter 4) displays a great range of volcanic features found under a thin (but nonzero) atmospheric pressure. In contrast, the elevated pressure environment found on both Earth's seafloor and the surface of Venus leads to interesting similarities, as well as some important differences, between the volcanic landforms observed in both locations (Chapter 5). Eruption into a near vacuum characterizes the volcanic features seen on the Moon and Mercury (Chapter 6) as well as Jupiter's moon Io (Chapter 7), but the ongoing tidal forcing on the latter makes it the most volcanically active object in the solar system other than Earth. Basaltic

Environmental Effects on Volcanic Eruptions: From Deep Oceans to Deep Space.
Edited by Zimbelman and Gregg, Kluwer Academic/Plenum Publishers, New York, 2000.

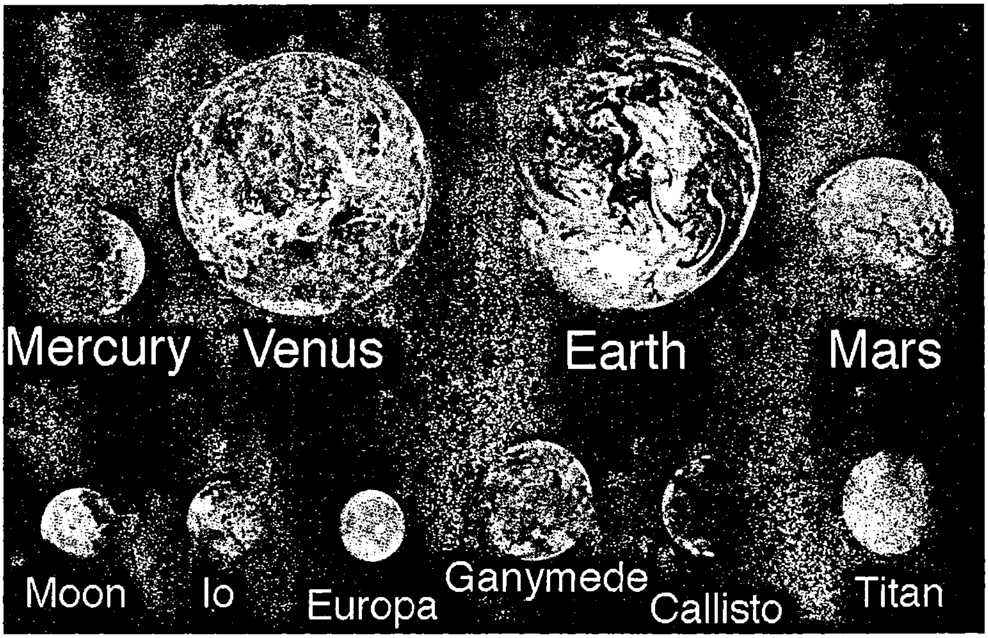

Figure 1.1. Sizes of the principal volcanic bodies in the solar system. Actual spacecraft images are shown at the same relative scale. NASA Public Affairs image P-41468.

Table 1.1. Basic Physical Parameters of Volcanic Planets and Moons

Object[a]	Mass (10^{22} kg)	Eq. radius (10^6 m)	Density (10^3 kg m^{-3})	Gravity (m s^{-2})	Surface atm. pressure (10^5 N m^{-2})	Surface temp. (K)
Mercury	33.01	2.439	5.44	3.70	~0	90–740
Venus	486.8	6.051	5.24	8.87	~90	740
Earth	597.4	6.380	5.52	9.81	1	190–338
Moon	7.35	1.738	3.34	1.62	~0	100–360
Mars	64.18	3.396	3.93	3.71	0.007	150–320
(Jupiter)	189900	71.492	1.33			
Io	8.93	1.821	3.53	1.80	~0	80–160
Europa	4.80	1.560	3.04	1.31	~0	80–120
Ganymede	14.8	2.630	1.94	1.42	~0	80–150
(Callisto)	10.8	2.400	1.86	1.25	~0	80–160
(Saturn)	56850	60.268	0.69			
(Titan)	13.5	2.575	1.86	1.36	1.44	~92
Enceladus	0.0084	0.250	1.24	0.09	~0	~60–145
(Neptune)	10240	24.764	1.64			
Triton	2.14	1.350	2.06	0.78	0.000014	~38

[a] Natural satellites are indented below primary planet. Names in parentheses are included for comparison only; they are not necessarily volcanic objects.

lavas are probably most common on the planets mentioned above, but the possibility of more rare "exotic" lavas illustrates that volcanic activity is not limited to common silicate lavas (Chapter 8). The book closes with a brief summary and a compilation of physical parameters important for modeling volcanic phenomena (Chapter 9). As an aid to understanding these diverse topics, we next briefly discuss several themes encountered in the subsequent text, highlighting aspects the reader should note while progressing through the book.

1.2. ENVIRONMENTAL EFFECTS ON VOLCANISM

Understanding the relation between the environment and volcanic processes and products is the primary objective of this book. It is important to be aware of the many ways in which the environment can exert a strong influence on several aspects of a volcanic eruption. The "environment" consists of a complex array of factors, each of which contributes differently to the physical condition encountered by erupted volcanic products. Some of the factors that are likely to be the most significant in terms of affecting the condition and state of lava or pyroclastic materials are highlighted below.

Temperature. The rate of cooling of a lava flow has a significant effect on both the morphology and the emplacement condition of lava. When the lava temperature is several times that of the surrounding environment, rapid quenching generates a glassy crust that provides important insulation to the fluid lava beneath the crust (see Chapters 2, 4, and 5). Cooling is dominated by radiation when the lava is in a thin to nonexistent atmosphere (Chapters 6 and 7), but a thick atmosphere or seawater may actually increase the cooling rate through advection or convection in the surrounding fluid (e.g., Wilson and Head, 1983; Chapter 5). If the surroundings are maintained at a high temperature, as on Venus, the elevated temperatures may reduce the effective strength of the rock both in a lava flow and in the underlying country rock (Chapter 5). Eruption temperatures may range considerably, depending on the lava composition (e.g., komatiites apparently had eruption temperatures more than 200°C greater than those of typical basalts; see Chapters 7 and 8).

Pressure. Vesiculation can be modified by external pressure. For example, pressure from the overburden of seawater (Chapter 5) or ice (Chapter 3) inhibits vesiculation in erupting lavas, and a similar phenomenon occurs on Venus (Chapter 5). High atmospheric density, such as exists on Venus, may also contribute to convective cooling, as mentioned above. Ambient pressure, in conjunction with temperature, might affect the stability of mineral phases, which in turn might affect the solidification of lava or pyroclastic materials.

Gravity. The acceleration of gravity is the basic source behind most body forces experienced by volcanic products once they have left the vent. The magnitude of this force will affect all of the rates associated with emplacement of either fluid lavas or pyroclastic particulates. This value ranges over two orders of magnitude for the objects summarized in Table 1.1, which must have consequences for the resulting volcanic landforms and deposits found on their surfaces (Chapters 2, 4–7).

Slope and Roughness. The relief and texture of the surface onto which an eruption takes place will influence the emplacement of the volcanic materials. Slope, in conjunction with the acceleration of gravity, vectorially resolves some fraction of the downward force of gravity into a force for movement over the surface. The roughness of the underlying surface, when comparable to the thickness of the flow, can similarly affect emplacement by retarding the effects of the downslope motive force. These effects will be most important for prolonged eruptions of relatively limited effusion rate, as opposed to large effusion rates that would rapidly emplace lavas irrespective of local relief (see Chapters 2 and 5).

Meteorology. Where an eruption takes place into an atmosphere, motion of that atmosphere can contribute to the emplacement of the products. This is most important for pyroclastic eruptions where dispersal patterns conform to any prevailing wind (Chapters 2 and 4). Eruptions into near-vacuum conditions clearly would not experience such effects (Chapters 6 and 7).

Composition. The composition of the surrounding bedrock and atmosphere, as well as that of the erupting magma, might influence the volcanic products. Differing equilibrium and nonequilibrium reactions become possible, depending on the specific materials involved. The presence and state of water is a major factor for subaqueous and subglacial eruptions (Chapters 3 and 5).

Other Factors. Certainly factors in addition to those mentioned above help to characterize various planetary environments. However, some of these additional environmental factors likely do not have a significant influence on volcanic eruptions. For example, here we will not deal with the presence or absence of electromagnetic fields and energetic particles, a situation that varies greatly throughout the solar system depending on the presence and strength of a planetary magnetic field. All such environmental factors that are unlikely to have an impact on volcanic phenomena are excluded from what we consider here to be the environment of an eruption.

1.3. LAVA COMPOSITION

Most of the volcanism discussed in this book involves basalt, the most common rock on Earth and, it is presumed, on many other planetary surfaces as well (Basaltic Volcanism Study Project, 1981). It is important to realize that only for Earth (Chapter 2) and the Moon (Chapter 6) do we "know" that the dominant volcanic material is basalt; these are the only two extraterrestrial objects from which documented samples of basalt have been collected and analyzed. There is a suite of meteorites whose trapped gases indicate an origin on Mars, and these meteorites include several examples of basalts (Chapter 4), but unfortunately we do not know where on Mars the meteorites came from. In spite of these limitations, it is still widely held that basalt is likely to be the dominant volcanic rock not only on Earth, but also throughout the inner solar system, and even out to at least one moon of Jupiter, Io (Chapter 7). From remote sensing studies we know that the reflected and emitted electromagnetic radiation from most planetary volcanic materials is at least consistent with a basaltic composition, even if we cannot as yet remotely determine the precise mineralogic makeup of planetary surfaces. The volcanism discussed in this book is primarily basaltic volcanism except where otherwise noted.

Many existing remote sensing techniques are more sensitive to surface textures than to compositional variations. Not all "dark" (low albedo) rocks are likely to be basalts. Even where we are confident that we are indeed looking at volcanic rocks, our compositional inferences are commonly related to textural details or gross topographic properties that are not particularly diagnostic of composition. The observed surface textural properties may be more closely related to the specific physical situation during emplacement than to compositional variations. A significant compositional unknown, even if we are dealing primarily with basaltic magmas, is the volatile content and constituents. The limited samples currently available from other planets do not provide strong constraints on the type and abundance of volatiles actually present in extraterrestrial lavas. Since volatile abundance and type may have a significant impact on eruption and emplacement mechanisms (Chapters 2, 4, and 8), the reader should be cognizant of the limitations to our present models and theories.

We conclude this brief discussion of lava composition by considering viable alternatives to the silicate magma presumed to dominate throughout much of the solar system. Carbon-rich volcanic products are a rare but still important part of the terrestrial volcanic record (Chapter 8), and such magmas might have played a role in some volcanic features present on Venus and Mars. Sulfur flows are also rare but documented on Earth, and were a favored alternative for some flows on Io (although recent temperature measurements reduce the likelihood that sulfur flows comprise a substantial part of the volcanic record on this moon—see Chapter 7). Water and even ammonia act as magma in the cold temperatures of the outer solar system (Chapter 8), and at the extreme edge of the solar system, vaporizing nitrogen powers geysers on the frigid (38 K) surface of Triton (McKinnon and Kirk, 1999). These examples should encourage us to keep an open mind with regard to both the prevalence of basaltic volcanism and how the conditions in the distal portions of the solar system fundamentally alter our concept of "magma" and "volatile."

1.4. LAVA RHEOLOGY

Similar to the tacit assumption that most extraterrestrial volcanism in the inner solar system is basaltic, we also assume that the majority of extraterrestrial lava flows have a rheology consistent with our current understanding of the behavior of basaltic magmas. It is challenging to obtain measurements of rheologic parameters in actively flowing lava (e.g., Pinkerton, 1993), whose high temperatures make it hard on both the instrumentation and the humans involved. Yet an accurate understanding of lava rheology is crucial to a complete description of lava emplacement, which in turn is the current limit on our ability to model the details of flowing lava. Laboratory measurements of melted volcanic rocks and simulants that mimic the bulk properties of lava are providing important insights about flowing lava (Figure 1.2), yet in the laboratory it is difficult, if not impossible, to re-create the actual volatile and crystal content of fresh lava, both of which contribute to its overall rheologic properties (e.g., Dragoni, 1993). There is also a great need for laboratory and field studies of nonsilicate lavas, some of which may behave quite different from "typical" basalt flows (see Chapter 8). Add to this the complete lack of information about the rheologic properties of extraterrestrial lava flows and you begin to see how serious is this deficiency in our current state of knowledge, since morphology is not as yet indicative of *unique* composition and rheology information.

In spite of these limitations, we can still appreciate some of the physical parameters that are important contributors to lava rheology. These include, but are not limited to, composition (with all of the caveats discussed in the previous section), temperature (both of the lava and of the surroundings, as well as the temperature gradient across the growing solidified crust), volatile content (both the abundance and the composition of the volatiles), crystal content (abundance, size, and size distribution), flow rate and slope (both of which contribute to the rate of shear experienced throughout the flow), and flow front characteristics (perhaps the least understood of all factors). Flow front dynamics are important for assessing how fresh liquid lava is supplied to the growing flow, which varies greatly between pahoehoe and a'a flows, for example. The reader should keep such factors in mind whenever lava rheology is discussed throughout the book.

Figure 1.2. A laboratory simulation of lava flow emplacement using carbowax in a sugar water solution that reproduces the essential rheologic properties of flowing basalt. Lines on the floor are 2 cm apart; vent is to the left. Solid wax is light; liquid wax is dark. Courtesy of Jonathan H. Fink, Arizona State University, and Tracy K. P. Gregg, SUNY-Buffalo.

1.5. EMPLACEMENT STYLES

The manner in which volcanic materials are emplaced can be as important as the nature of the volcanic materials themselves. Pyroclastic materials are by definition the result of explosive ejection that disrupts the rising magma into small clots and particles, but the size distribution of the resulting materials is closely related to the explosive intensity and magma supply rate to the vent. For lava flows, effusion rate remains a controversial but still fundamental factor to emplacement. Hawaiian subaerial flows have been documented with effusion rates of tens to hundreds of cubic meters per second, with pahoehoe flows comprising practically all flows $<10\ m^3\ s^{-1}$ (Rowland and Walker, 1990; see Chapter 2). In spite of our familiarity with Hawaiian-style eruptions, they may not be typical of eruptions on a planetary scale. For example, volcanism along midocean ridges is likely the dominant way in which lava is emplaced on our planet, and yet no seafloor eruption or lava flow has been observed during emplacement (see Chapter 5). The largest effusion rate for a historic eruption is likely that of the Laki eruption in Iceland where fissures supplied $\sim 4 \times 10^4\ m^3\ s^{-1}$ of lava at peak discharge (Thordarson and Self, 1993), which may be more indicative of midocean ridge volcanic activity. Effusion rates for extraterrestrial lava flows can only be inferred from final flow dimensions; such estimates range from $\sim 10^2$ to $10^7\ m^3\ s^{-1}$ but concentrate around $\sim 10^5\ m^3\ s^{-1}$ (Zimbelman, 1998).

The question of effusion rate is directly related to the broader issue of whether the emplacement was "fast" or "slow" (see Chapter 2). Advocates of fast emplacement traditionally were required to invoke turbulent flow, although recently this requirement has been dropped because of chemical and field-related arguments (Reidel, 1998). Advocates of slow emplacement use the mechanism of flow inflation to raise the flow crust and increase its resultant thickness severalfold (Thordarson and Self, 1998). This debate has spread to include seafloor flows (Gregg and Chadwick, 1996), and there is no a priori reason to exclude either option while considering flows in diverse planetary environments. The role of lava tubes in the emplacement of large flows is beginning to undergo quantitative evaluation and it too requires careful consideration for planetary applications.

Eruption of lavas beneath an ice cover is a specific example where the environmental situation may strongly influence the details of emplacement. Subglacial eruptions have led to well-documented cases of the sudden release of large volumes of meltwater, called *jökulhlaups* in Iceland (see Chapter 3). Unfortunately, it is not possible to observe directly how eruptions progress beneath the ice, but when exposed by the subsequent removal of the ice cover, distinctive deposits of hyaloclastites (essentially pyroclastic material strongly influenced by interaction with the meltwater surrounding a subglacial eruption), underlain by pillow lavas, are the common result (see Chapter 3). The interaction of volcanics and ice is also possible on Mars (Chapter 3) and the ice-rich satellites in the outer solar system (Chapter 8).

1.6. ENVIRONMENTAL IMPACT OF VOLCANISM

Much of the above discussion has centered around how volcanic materials interact with their surroundings on leaving the volcanic vent. However, it has also become clear that volcanic eruptions can in themselves influence and alter their surroundings. This situation is most often cited for the consequences of very large subaerial volcanic eruptions that may result in a pronounced, if temporary, effect on regional and even global climate (see Chapter 2). Both acidic aerosol components and quantities of greenhouse gases released during a large eruption can contribute to climatic effects, some of which can be devastating to agriculture and its dependent human population (Thordarson and Self, 1993). Pyroclastic flows also may generate a local environment around the rapidly traveling cloud of heated gas and particulates (see Chapter 2). This is perhaps most dramatic for the long-lived large eruptions occurring on Io, where localized column collapse and pyroclastic flow generation may produce local environments substantially different from the normal Ioian conditions (see Chapter 7). There is great potential for synergy between studies of terrestrial and planetary eruptions in evaluating their potential impact on the regional and global climate; each area of investigation likely can learn much from the other, and hopefully this book can contribute to this process.

1.7. CONCLUSION

When the reader has reached the end of this book, we hope that he or she will go away with the thought that the environment may significantly modify compositional and rheologic constraints on lavas. Traditional geologic training emphasizes the dominant role of magma composition on volcanic mechanisms and resulting landforms, with physical variations often attributed to rheologic changes to the flowing lava. Here we do not contest this view, but we hope that the solar system perspective provides readers with a range of examples in which they can judge for themselves the degree to which magma properties may be affected by the environment into which the eruption takes place. The wealth of new information obtained from many planetary spacecraft, as well as continuing investigations of both subaerial and subaqueous volcanism on Earth, has greatly expanded our range of "known" examples of volcanism. We have learned a lot, as reported in this book. However, we also still have a long way to go to understand fully the mechanisms and processes that cause a volcanic feature to look the way it does (see Chapter 9).

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