Cryovolcanism: Ice as Lava

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Abstract. Cryovolcanism, a new branch of planetary volcanology, was recently discovered when Voyager 2 identified geyser-like plumes of nitrogen on Neptune's moon, Triton. Defined as the eruption of water and other liquid or vapor-phase volatiles onto the frigid surfaces of the outer solar system satellites, this form of exotic volcanism is a likely explanation for some of the volcanic-like features seen on the moons of Jupiter, Saturn, Uranus, and Neptune. Europa, Jupiter's smallest moon, appears to be bristling with signs of recent activity, and is suspected of having a liquid water ocean beneath a water ice crust, ideal conditions for cryovolcanic activity. In combination with its peculiar smooth and ridged plains, Europa has relatively few impact craters indicating that the surface is comparatively young, as little as 100 million years old. This suggests that resurfacing has occurred, or may be still occurring today in the far reaches of the solar system, in which case cryovolcanism may be the answer.

1. Introduction

The eruption of "ice" onto the surfaces of planetary bodies, in a manner not unlike silicate volcanism, seems a bit strange in the way of temperature and composition. However, cryovolcanism is compatible with the American Geophysical Institute definition of volcanism, which refers to the extrusion of molten rock without reference to composition. Water, ammonia, or methane ice mixtures, in combination with various other non-water components, are thought to behave similarly to silicate magmas under the extreme conditions of the outer solar system (Pinkerton, H., et al., 2000). This gives cryomagmas a wide range of viscosities and densities that make the formation of icy volcanic constructs possible.

The terrestrial analogs of cryovolcanism are the so-called "ice foots" on the shores of Lake Superior in North America. The waves there pump cold water up through open cracks in the ice, thereby forming icy mounds around the "vents." The geysers of Yellowstone National Park could also be considered, as they bring hot water to the surface. But these small scale features hardly compare to the typical silicate volcanoes on Earth, nonetheless they fit the description. One could argue that cryovolcanism, in the sense of planetary science, is geared more toward the eruption of water in a solid state than in the liquid state, because the extrusion of liquids would be frozen solid at frigid planetary surface temperatures.

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2. Cryomagmas

Two conditions must exist for cryovolcanism to take place on the icy satellites: liquids must be generated in the interior, and then the melt must migrate to the surface. For this, the right planetary factors are needed: the size of the moon should be large enough for sufficient gravitational energy to generate heat for the melting of materials; the orbital history of the moon dictates the degree of tidal (or frictional) heating; the moon must have abundant water, along with a silicate fraction which determines radiogenic heating; and finally, the location in the solar system is important, which is directly related to composition and surface temperature.

Most satellites of the outer solar system are inferred to consist of large portions of water ice, based on their bulk densities and spectral properties (Clark et al., 1986; Schubert et al., 1986). Unlike silicate rocks and minerals, ice undergoes a volume reduction upon melting. Liquid water magmas should not rise through an ice crust, but are instead expected to sink. This proposes a profound problem with the buoyant-rise mechanism that commonly operates in silicate magmas. Other means must deliver melt to the surface, like a change in density to produce a positively buoyant force. Contamination of the ice can provide the necessary differences in density; the non-water components and dissolved gases also alter magma viscosity and rheology.

Other mechanisms could provide a means of delivering material to the surface. Figure 1 shows the possible configuration of the internal structure of a satellite such as Europa. Volatiles like carbon dioxide dissolved within a melt would behave similarly in ice as it would in

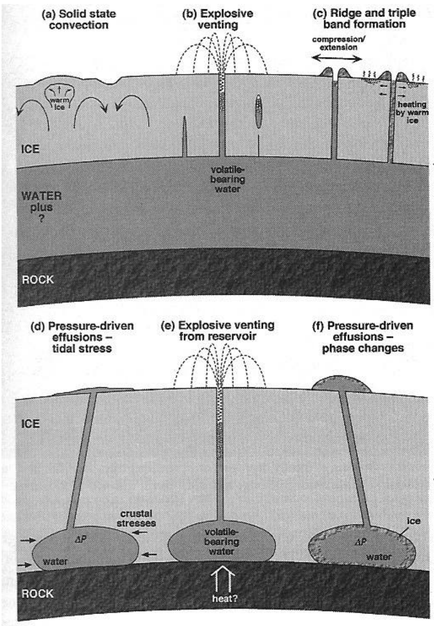

Figure 1. Possible internal structure on Europa. (a) Diapirism associated with solid-state convection. (b,e) Explosive exsolution of volatiles by depressurization. (c) Water exposed and frozen during tidal opening and closing of fractures, (d) or volume changes (f) associated with ice crystallization. Diagram not to scale. (Pinkerton, H., et al., 2000)

silicate magmas. As icy material rises through a conduit, the gases would exsolve to drive a violent cryoclastic eruption. If the pressure exerted on a water body by ice overburden is released during the opening of a fissure in the ice, bubbles of gas will nucleate and grow rapidly by decompression and coalescence (Sparks, 1978). This would result in a stream of gas and water droplets being ejected into the near-vacuum of space where the particles would follow ballistic paths forming an umbrella-like plume.

In the absence of buoyancy or volatiles, the pressurization of isolated liquid bodies may drive an eruption. Perhaps enough pressure could be attained through volume changes associated with phase changes in a magma reservoir. Tidal flexing of an entire satellite could lead to the generation of a combination of overpressure in the water and stresses in the ice layer that produce fracturing, forcing water to rise through the fractures.

Possible compositions and internal heat sources on the icy satellites suggest that resurfacing can occur through eruptions of water in combination with various other non-water components, in a solid, slushy, or liquid state, or as gas driven particle sprays (Pinkerton, H., et al., 2000).

3. Europa

The first close ups of icy satellite surfaces were provided by the Galileo mission, which began studying the Jupiter system in 1995. Although no direct evidence of volcanic activity has been documented on Europa (Figure 2), it has many promising features that indicate resurfacing activity. Voyager 2 images (1979) revealed two main units on the surface of the moon: bright uniform plains, and dark wedged-shaped features. Dark mottled terrain is thought to be muddy ice that has erupted or intruded into the surface. Additionally, the scarcity of impact craters on Europa's surface is significant in understanding the geologic processes that work to erase them.

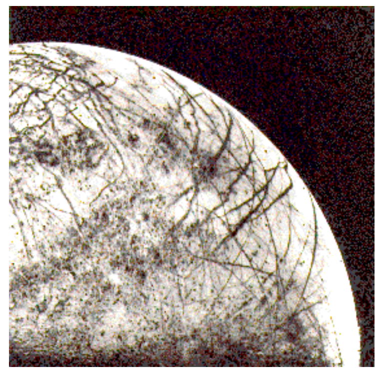

Figure 2. Voyager 2 image of Europa, 1979.

Europa is largely made up of silicates, is considered differentiated, and has an albedo of ~0.64, consistent with water ice. Because Europa is caught in a tidal "tug-of-war" between Io and Ganymede, suggests a sufficient amount of energy to maintain a molten layer of liquid water beneath an icy surface, perhaps a global ocean (Ojakangas and Stevenson, 1989) extending to depths of 50 to 150 km below the surface (Geissler, P., 2000). The idea of a subsurface ocean is also based in part by Europa's lack of topography; its greatest peaks reach heights of only a few hundred meters, and the largest craters excavate to even shallower depths (Geissler, P., 2000).

There are many features with possible volcanic origins on Europa, and here only a few will be mentioned as proposed by H. Pinkerton, et al., 2000. Ridges several kilometers long dominate the crust, and are attributed to the tidal opening and closing of fractures where ice and slush erupt like linear fissures. The formation of triple bands, lineaments consisting of a bright central stripe flanked by broader dark margins, are considered to be evidence for block faulting and flooding. Lenticulae, circular or elliptical features with various textures and relief, and also domical features, are thought to be the surface expression of diapirism associated with solid-state convection, or buoyant ice. Lobate flow-like features are suggestive of effusive eruptions of a liquid with significant viscosity or yield strength. It is also possible that ices could be superheated by volcanism occurring in the underlying silicate rock layer, therefore melting the ice above it forming the flat smooth areas, or maculae (Figure 3).

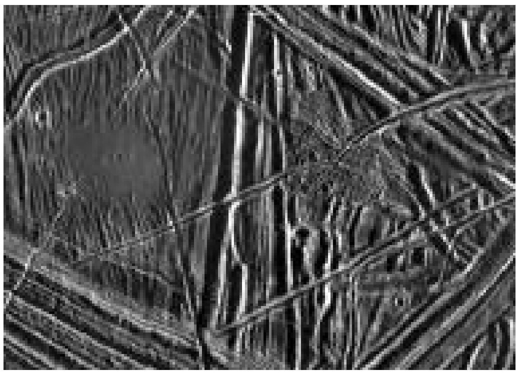

Figure 3. The "puddle" on Europa.

The origins of Europa's perplexing surface features are still widely debated, and all ideas are inferred from observations. The existence of a liquid layer on Europa is by no means proven, and will be debated for many years to come. However, the possibilities of a subsurface ocean, and perhaps seafloor silicate volcanism cannot be ruled out by the new data, and might have profound implications for the likelihood of finding life on the icy world (Geissler, P., 2000).

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