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Explosive volcanic eruptions on Mercury: Eruption conditions, magma volatile content, and implications for interior volatile abundances

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ABSTRACT

Images obtained by the MESSENGER spacecraft have revealed evidence for pyroclastic volcanism on Mercury. Because of the importance of this inference for understanding the interior volatile inventory of Mercury, we focus on one of the best examples determined to date: a shield-volcano-like feature just inside the southwestern rim of the Caloris impact basin characterized by a near-central, irregularly shaped depression surrounded by a bright deposit interpreted to have a pyroclastic origin. This candidate pyroclastic deposit has a mean radius of ~24 km, greater in size than the third largest lunar pyroclastic deposit when scaled to lunar gravity conditions. From the extent of the candidate pyroclastic deposit, we characterize the eruption parameters of the event that emplaced it, including vent speed and candidate volatile content. The minimum vent speed is ~300 m/s, and the volatile content required to emplace the pyroclasts to this distance is hundreds to several thousands of parts per million (ppm) of the volatiles typically associated with pyroclastic eruptions on other bodies (e.g., CO, CO_2, H_2O, SO_2, H_2S). For comparison, measurements of the exsolution of volatiles (H_2O, CO_2, S) from basaltic eruptive episodes at Kilauea volcano, Hawaii, indicate values of ~1300–6500 ppm for the terrestrial mantle source. Evidence for the presence of significant amounts of volatiles in partial melts derived from the interior of Mercury is an unexpected result and provides a new constraint on models for the planet's formation and early evolution.

1. Introduction

The planet Mercury is generally thought to be deficient in interior volatiles compared with the other terrestrial planets (e.g., Boynton et al., 2007). Numerical simulations of planetary accretion indicate that Mercury is likely to be dominated by material formed in the inner solar nebula (Wetherill, 1994), where temperatures were comparatively high and volatile species remained in the gas phase throughout the time interval when nebular gas was present (e.g., Boss, 1998; Chambers, 2005). Several of the scenarios proposed to account for Mercury's anomalously high bulk density (and inferred high ratio of metal to silicate) involve one or more episodes of further heating, either by the nebula itself (Cameron, 1985; Fegley and Cameron, 1987) or as a result of collision with another large object (Wetherill, 1988; Benz et al., 1988, 2007). Such heating should further deplete volatile species in Mercury's interior (Boynton et al., 2007). Moderately volatile alkali metals are known to be important surface-derived species in Mercury's exosphere (Potter and Morgan, 1985, 1986), and polar deposits postulated to consist of water ice have been documented by Earth-based radar on the floors of permanently shadowed impact craters near Mercury's poles (Harmon and Slade, 1992; Slade et al., 1992); these volatiles may be derived dominantly from meteoritic and cometary sources (e.g., Moses et al., 1999; Leblanc and Johnson, 2003), however, and need not constrain interior volatile abundances.

An important new constraint on interior volatile abundances on Mercury comes from imaging conducted during the first flyby of Mercury by the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft (Solomon et al., 2008). MESSENGER images of the 1550-km-diameter Caloris basin reveal several irregular depressions surrounded by bright, relatively red deposits (compared to Mercury as a whole). Detailed assessment of morphologic characteristics indicates that these features are broad, low shield volcanoes (Head et al., 2008, 2009a-this issue). By analogy with similar features on the Moon, the haloes of diffuse-bordered, high-reflectance material surrounding several of these irregular depressions are interpreted as pyroclastic deposits (Head et al., 2008, 2009a-this issue), which are the product of explosive volcanic eruptions driven by the exsolution of magmatic volatiles during ascent of the magma from the mantle or lower crust (e.g., Wilson and Head, 1981). These volcanic features therefore provide evidence for volatiles in Mercury's mantle or lower crust at the time of magma genesis.

In this paper we offer a detailed rationale for the identification of pyroclastic deposits on Mercury, some inferences on eruption

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conditions and magmatic volatile contents consistent with the geometry of observed deposits, and an assessment of the implications of these findings for the volatile budget of Mercury's interior. We begin with a summary of what is known of pyroclastic deposits on the Moon as a basis for comparison with features on Mercury; we pay particular attention to possible causes for spectral and albedo differences between pyroclastic deposits on the Moon and Mercury. We then provide a detailed examination of a type example of pyroclastic deposits on Mercury. We derive estimates of the eruption velocity and the volatile content of the magma consistent with such estimates for candidate volatile species. We summarize constraints on Mercury's formation history and volatile inventory, and we discuss how the identification of pyroclastic eruption conditions on Mercury provides new constraints on these issues.

2. Characteristics of pyroclastic deposits on the Moon

Local and regional deposits interpreted to be of pyroclastic origin have long been recognized on the Moon (Wilhelms and McCauley, 1971; Scott et al., 1977), generally in association with irregular depressions, sinuous rilles, or fractures in large crater floors (Head, 1974; Lucchitta and Schmitt, 1974; Wilson and Head, 1981; Gaddis et al., 1985; Hawke et al., 1989; Weitz et al., 1998; Weitz and Head, 1999; Gaddis et al., 2003). Regional deposits are the most areally extensive (areas greater than 1000 km^2) and are commonly located on uplands adjacent to younger mare deposits (e.g., Head, 1974; Weitz et al., 1998). Localized deposits, in contrast, are smaller in extent and more widely distributed across the lunar surface (Head, 1976; Hawke et al., 1989; Coombs et al., 1990). The albedo of lunar pyroclasts is generally low, although some deposits have a slightly higher albedo (perhaps due to intermixed mature lunar highlands material), such as those at J. Herschel and Orientale (Gaddis et al., 2003). Indeed, the low albedo of lunar pyroclastic deposits has long been part of their definition, and the deposits are often called lunar dark mantle deposits or material (Pieters et al., 1974; Weitz et al., 1998).

Surface geological exploration at the Apollo landing sites and multispectral telescopic observations of the dark mantle deposits indicate that they are composed of submillimeter volcanic glasses or crystallized beads. The reflectance spectra of the lunar pyroclastic deposits are influenced by their style of emplacement and cooling, chemical composition, grain size distribution, and age. For example, the Taurus–Littrow deposit spectrally matches the crystallized black beads that were collected at the Apollo 17 landing site (Pieters et al., 1974), whereas the Aristarchus Plateau deposit is dominated by orange and red glasses (Zisk et al., 1977; Lucey et al., 1986). Remote-sensing data for numerous more localized deposits (Hawke et al., 1989) show evidence for three compositional groups, each reflecting variation in the eruption conditions associated with their emplacement. The effects of various eruption conditions are discussed in detail in the next section.

Depending on their chemical compositions, lunar volcanic glasses may have a variety of colors, including clear, red, orange, brown, yellow, and green (Delano, 1986). Absorptions at optical wavelengths are dependent on electronic transitions associated with ferrous iron in silicates, which generally lowers the reflectance due to overlapping ultraviolet (UV) and near-infrared (NIR) bands and produces an absorption feature at wavelengths near 1 μm (e.g., Burns 1993; Lucey et al., 1998). The combined presence of Fe and Ti can lower the albedo due to Fe–Ti charge-transfer bands, while low-Ti glasses, such as the Apollo 15 green glasses, do not have low reflectances at visible wavelengths (Bell et al., 1976; Wells and Hapke, 1977; Lucey et al., 1998). Orange glasses tend to have a steeper (or “redder”) spectral slope at visible and NIR wavelengths because they have an abundance of TiO_2 (Gaddis et al., 2003). In contrast, the titanium in black pyroclastic beads is incorporated during crystallization into the mineral ilmenite ($FeTiO_3$), which crystallizes inside the glass as laths and gives black beads a low-reflectance, more shallowly sloping (or “bluer”) spectrum that closely resembles that of bulk ilmenite (Pieters et al., 1974; Weitz et al., 1998).

Many lunar pyroclastic samples contain large amounts of FeO (16.5 to 24.7 wt.%) (Delano, 1986). However, the surface of Mercury appears to be depleted in silicates containing ferrous iron because reflectance spectra largely lack the distinctive absorption feature near 1 μm (e.g., Vilas, 1988; Warell, 2003; Warell and Blewett, 2004; Warell et al., 2006; McClintock et al., 2008; Robinson et al., 2008). Despite the dearth of ferrous iron in silicates, Mercury's surface nonetheless darkens and reddens with time like that of the Moon. This darkening and reddening has been interpreted to be the result of production of nanophase iron (e.g., Pieters et al., 2000; Hapke, 2001), which could be derived from an opaque phase in the crustal material or from delivery by micrometeorite impacts (Noble and Pieters, 2003). On the Moon, deposits that are brighter and redder than the average Moon spectrum appear to be lower in iron (e.g., highland material); deposits that are darker and redder than average are higher in iron (e.g., low-Ti mare material) (Lucey et al., 1995). Crater ray materials on Mercury are brighter and bluer than the general Mercury spectrum, indicating that they are younger, and thus not yet as space weathered. The enigmatic “bright crater floor deposits” (Robinson et al., 2008) are also bright but with an even bluer relative spectrum. Deposits that are darker and bluer than average for Mercury are interpreted to be higher in opaque minerals (potentially ilmenite) than other units (Robinson et al., 2008; Blewett et al., 2009-this issue). By analogy, pyroclasts on Mercury would be expected to be brighter and redder than surrounding units if they had less ferrous iron, titanium, and opaque minerals, or darker and bluer than surrounding units if the magma were relatively opaque-rich (or if some Fe and Ti were available). If the nanophase iron produced during space weathering is derived from iron-bearing phases on the surface, pyroclastic deposits with lower iron content and few iron-bearing opaque minerals would darken less during space weathering than more iron-rich deposits and thus remain brighter over time. If the iron is delivered to the surface by micrometeoroid bombardment, the deposit would be expected to darken at rates similar to other deposits.

Decreasing grain size generally increases visible reflectance. The properties of the magma source and the proportion of volatiles present in a pyroclastic eruption can influence the grain size of the deposit (Wilson and Head, 1981), as discussed below.

3. Formation of pyroclastic deposits

Pyroclastic eruptions take place when volatile species in rising magma exsolve at reduced pressure. Enough energy must be available both to convert the volatile phase to a gas and to overcome the viscosity of the host liquid and allow gas bubbles to grow. Depending on the characteristics of the magma, the nucleation of many bubbles can be favored or, alternatively, the continued growth of several large bubbles may occur. Bubbles nucleate and grow as the magma rises until they reach the point at which the bubble walls cease to deform plastically and shatter, resulting in fragmentation and ejection from the vent (Wilson and Head, 1981). The thin walls of the bubbles and the inter-bubble liquid become the resulting pyroclasts. The size of the pyroclasts is thus related to the bubble size, which is controlled by several parameters, including the volatile content of the magma, the magma viscosity, and its temperature (Wilson and Head, 1981). Roughness and irregularities in the vent can also contribute to the nucleation of bubbles, because pockets of roughness create sporadic zones with slightly less pressure, allowing bubbles to nucleate at somewhat lower temperatures or greater depths. The difference in spectral characteristics expected on Mercury as a result of grain size is thus difficult to predict.

Spectral and morphological differences among pyroclastic deposits may also be due in part to different eruption styles, which lead to