VOLCANIC ERUPTION PROCESSES ON MERCURY. L. Wilson[1] and J. W. Head[2] [1]Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK (L.Wilson@Lancaster.ac.uk) [2]Department of Geological Sciences, Brown University, Providence, RI 02912, USA.

Introduction: The presence, nature, distribution and importance of volcanism in the geological and thermal evolution of Mercury have long been debated [1-4]. New data from MESSENGER on the presence, absence, and distribution of various specific volcanic landforms and units [5], together with information on Mercury's crustal composition [6], allow us to model the generation, ascent and eruption of magma on Mercury. We assess melting processes, melt volumes and eruption conditions for two end-member options: the (a) presence [7-9] or (b) absence [10] of internal convection.

Melt generation: *(a) Convection present*. The variation of mantle temperature with pressure in a zone of pressure-release partial melting is essentially independent of planet size [11], and so if bodies have similar enough bulk compositions that the temperature range over which melting occurs is the same, then the pressure range will also be the same. But pressure increases with depth in a planet in proportion to the acceleration due to gravity, and to a first approximation acceleration due to gravity is proportional to body size. Thus in a smaller body the same pressure range requires a greater range of depths, and a larger vertical extent of the mantle will be involved, in inverse proportion to the radius, in generating the melts that form the crust. Partial melting over an ~ 85 km vertical depth range in the Earth's mantle [12] scales to ~220 km for Mercury's mantle and implies a volcanically-generated crust ~2.2 times thicker on Mercury than Earth.

(b) Convection absent. The poor thermal conductivity of silicates causes a radioactively-heated planet's interior to have a slowly-increasing temperature beneath a conductively controlled thermal boundary layer of depth B = ~1.4 $(\kappa\ \tau)^{1/2}$ [13] where τ is the time since planet formation and k is the thermal diffusivity of silicates, ~10^{-6} m^2 s^{-1}. For example, after 300 Ma B is ~130 km and after 1 Ga B is ~240 km. Thus even if a magma ocean is formed by rapid terminal accretion, its presence is less important than the deeper, post-formation internal temperature [11]. Peplowski et al. [14] used gamma-ray data from MESSENGER to measure near-surface abundances of U, Th and K on Mercury and infer the internal heat production rate. We approximate their results by $H = H_0 \exp(-\lambda\ \tau)$ where H is the heat production rate per unit volume, $H_0 = 1.18 \times 10^{-7}$ W m^{-3}, $\lambda = 1.1 \times 10^{-17}$ s^{-1}, and τ is time from planet formation, and use H in a numerical model of [13] to derive the temperature as a function of depth and time for a given initial mantle temperature. Melting starts when the temperature at any depth crosses the mantle solidus, T_s (in Kelvins), assumed to vary with pressure, P (in GPa) as $T_s = 1393.881 + 132.899\ P - 5.104\ P^2$ [15]. For an initial mantle temperature near 900 K, melting starts after ~800 Ma at a depth of ~220 km and the top of the melt zone progressively rises to ~90 km.

Thus whether mantle convection is present or absent on Mercury, vertically extensive planet-wide zones of partial melting should be present in the first half of its history, with variations in timing of onset, peak melt production and cessation as a function of the planetary formation conditions. In both cases, large volumes of mantle melt are available for eruption. The presence of extensive lava plains and absence of major shield volcanoes and volcanic rises [5] suggests that flood-volcanism dominated on Mercury, with mantle partial melts collecting at a density or rheological boundary near the mantle-crust interface and erupting directly to the surface [16].

Magma Transport Through the Crust: If the crust of Mercury consists largely of solidified mantle melt, the crust density ρ_C should be ~10% greater than typical melt density β and the melt density should be ~20% less dense than the mantle density ρ_M. However, magma gas vesicles cause crusts consisting of accumulated volcanics to be much less dense than coherent rock when a significant atmosphere is absent, as on Mercury, even if only small amounts of volatiles are present [17]. Crustal density increases with depth due to compaction. In the case of Mercury the mean crust density may be close to the mean magma density averaged over the vertical extent of the crust. We have therefore explored the geometries of elastic dikes [18] penetrating through the crust and the magma flow rates through them for a range of plausible values of crust thickness, C, vertical extent of melt pond at the base of the crust, H, stress threshold for fracturing the crust, S, crustal elastic properties (Poisson's ratio, ν, and shear modulus at the top, μ_T, and base, μ_B, of the crust), magma viscosity η and wall friction factor f. The relationships are

$$(\rho_M - \beta) = S/(g\ H)$$
$$W_{AV} = [(1 - \nu)/\mu_B]\ C\ [(\rho_M - \beta)\ g\ H + C\ g\ (\rho_C - \beta)]$$
$$\nabla P = g\ [(\rho_C - \beta) + (H/C)\ (\rho_M - \beta)]$$
$$U_M = \mathrm{MIN}\{(W_{AV}^2\ \nabla P)/(12\ \eta),\ [(W_{AV}\ \nabla P)/(f\ \beta)]^{1/2}\}$$
$$L = [\mu_T/(1 - \nu)]\ W_{AV}\ g\ H\ (\rho_M - \beta)$$
$$F = U\ L\ W_{AV}$$

where U_M is the magma magma rise speed through a dike of mean width W_{AV}, ∇P is the pressure gradient driving magma flow, L is the length along strike of the surface fissure and F is the total erupted magma volume flux. Using values g = 3.7 m s^{-2}, C = 50 km, ν = 0.25, μ_T = 10 GPa, μ_B = 30 GPa, H = 3 km, ρ_M = 3400 kg m^{-3}, β = 2900 kg m^{-3}, ρ_C = 2950 kg m^{-3}, η = 30 Pa s, f = 0.03, we find that magma rises in a turbulent fashion at ~8 m

s^{-1} through a dike with mean width 18.5 m feeding a surface fissure of length 89 km from which ~13 × 10^6 m^3 s^{-1} of lava is discharged. Magma motion in dikes this wide will be turbulent for all magma viscosities up to ~1000 Pa s, covering the entire range from komatiite through basalt to basaltic andesite, and so these eruption conditions are independant of magma composition. Changing densities and crust thickness over plausible ranges results in a wide range of scenarios, but the vast majority of conditions that allow eruptions to happen at all lead to eruption parameters within a factor of 10 of those given here.

Surface Lava Flows: Many lobate scarps exist on Mercury's surface. Some displace pre-existing topography and are clearly crustal thrust faults [4]. Others have relationships with surface topography implying that they are lava flow fronts [16]. Elevation measurements across these imply flow thicknesses of several tens of meters [16]. The implied flow units of which these are the boundaries extend for tens to a few hundred km [5]. Lava flows on this scale on Earth characterize large igneous provinces and such flows commonly inflate after emplacement [19]. Thus we model the emplacement of flows with initial thicknesses in the range 10-100 m. Flows with these thicknesses and lengths are consistent with magma eruption rates of order ~10^7 m^3 s^{-1}, similar to those inferred for lunar mare eruptions [20]. The equivalent analysis of flow conditions to that in [20] can be applied. The lava flow speed U_L of a flow of depth D and density β is

$$U_L = \mathrm{MIN}\{(D^2\ \beta\ g \sin\alpha)/(3\ \eta),\ [(2\ D\ g \sin\alpha)/f]^{1/2}\}$$

where long-range surface slopes, α, on Mercury are ~5 × 10^{-3} radians [21]. Flows 10, 30 and 100 m thick would have had speeds of ~3.5, 6 and 11 m s^{-1} and would have attained lengths of 300 km in ~24, 14 and 8 hours, respectively. For flow units up to 100 km wide, these values correspond to total volume fluxes of 3.5 × 10^6, 1.8 × 10^7 and 1.1 × 10^8 m^3 s^{-1}, consistent the range of conditions deduced above for transport through the crust. The Reynolds number, Re, for such flows is

$$Re = (2\ D\ U_L\ \beta)/\eta$$

and for a magma viscosity of 30 Pa s the above flow solutions imply Re = 7 × 10^3, 3.6 × 10^4 and 2.2 × 10^5 for flow depths of 10, 30 and 100 m, respectively, all >~2000, indicating turbulent motion. Inversion of the Reynolds number formula shows that flows with thicknesses 10, 30 and 100 m would have been turbulent for all magma viscosities less than ~100, ~540 and 3300 Pa s, respectively, confirming that all basaltic and komatiitic flows would have been turbulent, and implying the potential for thermo-mechanical erosion of their substrates. Evaluation of the Grätz number [22] for these flows shows that, like lunar mare flows [20], their lengths were limited not by cooling but instead only by the volume of magma available for eruption.

Explosive volcanism: Explosive volcanic activity was not anticipated for Mercury, which was expected to be depleted in volatiles [23]. However, at least 39 deposits morphologically consistent with emplacement by explosive activity have been identified [24]. The sources of the deposits are rimless, generally irregular pits, ~5-45 km in diameter [24-26]. Consideration of the energetics of eruptions in a vacuum [26, 24] shows that to reach the observed deposit radii, mainly in the range 20-50 km, required the erupting magma to contain ~4000 to 12000 ppm CO or the equivalent (inversely proportional to the molecular weight) of other volatiles. Candidate volatiles depend on the oxidation state of Mercury's interior [27] and include CO, N_2, S_2, CS_2, S_2Cl, Cl, Cl_2 or COS (reducing interior, most likely) or CO, CO_2, H_2O, SO_2, or H_2S (oxidizing interior, less likely). Equilibrium release from ascending magmas of up to 12000 ppm volatiles is not expected given the current understanding of Mercury's composition and oxidation state [27]. Also the mechanism of formation of the pits associated with the deposits is unclear. This suggests that some process may be required to concentrate volatiles into the tops of ascending dikes that fail to breach the surface to form lava flows. The contrast between the small volumes of pyroclastics and the large volumes of flood lavas on Mercury is striking.

Summary: Theoretical treatment of the ascent and eruption of magma in the Mercury environment shows that eruption process are likely to differ from those on other terrestrial planetary bodies, consistent with the emerging geological observations from the MESSENGER mission [e.g., 28].

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