THE MASS FLUX OF VOLATILES FROM EFFUSIVE ERUPTIONS ON MERCURY. Ariel N. Deutsch[1], James W. Head[1], Stephen W. Parman[1], Lionel Wilson[1,2], Gregory A. Neumann[3], and Finnian Lowden[1], [1]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912, USA (ariel_deutsch@brown.edu), [2]Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK, [3]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA.

Introduction: Discovering that Mercury is volatile rich is one of the most exciting findings of the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission. Mercury has abundant and widely distributed pyroclastics indicative of volatile-rich eruptions [1–3] and intriguing hollows suggestive of devolatilization [4]. Mercury also has been extensively resurfaced by large, effusive lava plains (Fig. 1) [1, 5]. Similar lava plains on the Moon, the maria, are known to contain volatiles [6–7] and are estimated to have outgassed ~10^{16} kg of CO and S and ~10^{14} kg of H_2O, with the bulk of volatiles being released during peak mare emplacement ~3.5 Ga [8].

If effusive volcanism released substantial volatiles on the Moon [6–7], then it is possible that substantial volatiles were also effusively released on Mercury, albeit with different chemical species [9–12]. On the Moon, outgassed volatiles have been predicted to be cold-trapped at the lunar poles today [e.g., 8]. Given that Mercury is known to be volatile-rich [1–4, 9–12], we seek to understand the potential contribution of outgassing to volatile deposits, specifically for Mercury's volatile species. Here we analyze the flux of effusive volcanism on Mercury, and discuss the potential fate of outgassed volatiles and their relationship to volatiles observed in high-latitude cold traps [e.g., 13].

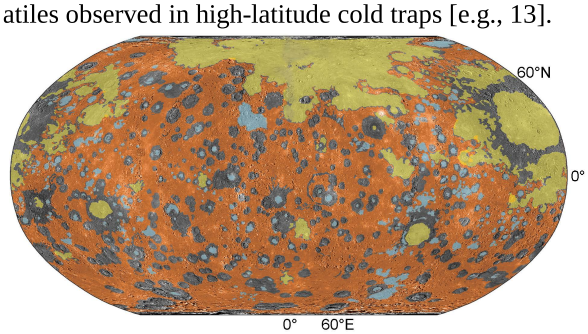

Fig. 1. Distribution of intercrater plains (ICPs; orange) [14] and smooth plains (SPs) [15] that have been dated (yellow) and not dated (blue) on Mercury.

Methods: Similar to the approach used for mare on the Moon [8], we estimate the fluxes of outgassed basalt and volatiles from effusive eruptions on Mercury.

Flux of effusive volcanism on Mercury. We estimate the volume of basalt released through time for all of the smooth plains (SPs), as well as for the intercrater plains (ICPs) (Fig. 1), which may also be large effusive flows that have since been modified by impacts [5, 14]. We explore three cases based on estimates of plains thicknesses: (1) minimum (assuming plains thicknesses, T, of 0.1 km [16]), (2) maximum (assuming T=3.5 km [16]), and (3) average (assuming T=1.1 km).

The timing of the SP and ICP eruptions are informed by previous analyses of unit ages when possible [5, 17–18]. We also estimate the ages of the three largest SP deposits that were previously undated from crater density statistics. From all of the dated terrains, we establish a production function of effusive eruptions on Mercury. The plains units that remain undated are distributed following this production function as a best estimate for when they formed. Using the surface age of plains units to describe the age of the entire deposit provides a maximum estimate of the volume of basalt effused at any single time.

Mercury's magmatic volatile content. Unlike of the Moon, we do not currently have any samples of Mercury's volcanic deposits, which would allow for the determination of the planet's degassed volatile content. Mercury has an extremely low oxygen fugacity (fO_2 estimated between IW-3 and IW-7), and laboratory experiments have thus far been limited in replicating both highly reducing conditions and high pressures characteristic of Mercury's interior. Here we use a variety of experimental petrology studies [19–21] to predict the dominant species and their abundances that may have been outgassed during effusive eruptions on Mercury (Table 1), although the actual volatile species present within Mercury's magmas remain unknown. We provide estimates for both low-gas (Model A) and high-gas (Model B) scenarios (Table 1).

	Estimated Abundance (ppm)			
	IW-3		IW-7	
Species	Model A	Model B	Model A	Model B
S [19]	100	1,000	700	7,000
CH_4 [20]	20	200	200	2,000
Cl [19]	130	1,300	170	1,700
N-H [20–21]	1	10	10	100

Table 1. Predicted volatile species for mercurian magmas. S abundances are estimated to be 1% of the estimated sulfur concentration at sulfide saturation (SCSS) for Model A and 10% of the estimated SCSS for Model B. CH_4, Cl, and N-H abundances for Models A and B are estimated from degassing contents of 10% and 100%, respectively.

Results: From the surface areas of SPs and ICPs (Fig. 1) [15], estimated plains thicknesses, ages [5, 14–18, 22], and volatile content [19–21], we estimate the total volume of effused basalt (Fig. 2) and the total mass of outgassed volatiles (Fig. 3) on Mercury.

Volume of effused basalts through time. The total volume of effused basalts estimated for Mercury's SPs ranges between ~2.3x10^8 and 7.9x10^8 km^3 depending on the estimated thicknesses of the plains (Fig. 2). If we consider the ICPs to also be large effusive flows, then the estimated volume nearly doubles (Fig. 2).

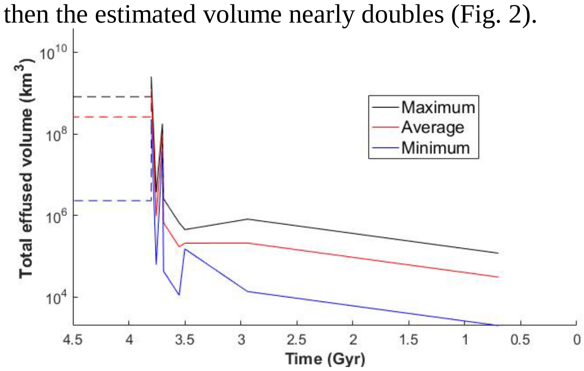

Fig. 2. Estimates of the total volume of effused basalts on Mercury over time for the SPs (solid) and ICPs (dashed). Note that the volume is shown on a log scale.

In a manner similar to the Moon, the flux of effusive volcanism on Mercury peaks ~3.8 Ga (Fig. 2) [15]. The production function of these eruptions relies on the estimates of plains ages, and many plains deposits are not yet dated (Fig. 1). The time-resolved flux in Fig. 2 represents a general trend in the production function of outgassed basalts on Mercury. Plains deposits are likely to have formed via multiple volcanic events [1, 5, 14–15] and the surface age of any unit does not accurately describe the timing of the entire deposit.

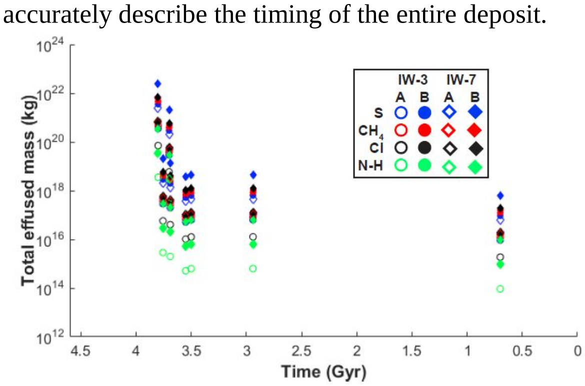

Fig. 3. Estimates of the total mass of effused S (blue), CH_4 (red), Cl (black), and N-H (green) on Mercury over time for SPs assumed to be of average thickness (red line in Fig. 2). Estimates are computed for low-gas (Model A) and high-gas (Model B) scenarios for fO_2 values of IW-3 and IW-7.

Mass of effused volatiles through time. Assuming an upper value of fO_2 for Mercury of IW-3, we estimate that ~10^{17} kg of S and Cl, ~10^{16} kg of CH_4, and ~10^{15} kg of N-H were outgassed during the formation of SPs in a low-gas scenario (Model A; Fig. 3). Assuming a lower fO_2 of IW-7 for Model A, we estimate that ~10^{18} kg of S, ~10^{17} kg of Cl and CH_4, and ~10^{16} kg of N-H were outgassed. For both fO_2 scenarios, these estimated values increase by an order of magnitude for a high-gas scenario (Model B; Fig. 3).

The fate of outgassed volatiles: We find that the volume of effusively outgassed basalts on Mercury is 2 to 3 orders of magnitude higher than that predicted for the Moon [8]. The most prevalent volatile species predicted for Mercury (S, CH_4, and Cl) are also 1 to 4 orders of magnitude more abundant than what is predicted for the most abundant volatiles outgassed on the Moon (CO, S, and H_2O) [8]. On the Moon, it has been predicted that effusively outgassed volatiles may have been present in sufficient volumes to produce a transient atmosphere capable of aiding in the transport of H_2O to cold-trapping regions [8]. At mantle pressures and Mercury's extremely reducing conditions, H_2O is not predicted to be present in the magma [e.g., 9–12]. But the fate of large volumes of volatiles other than H_2O is an important unanswered question. The large volumes of outgassed volatiles calculated here suggest that volcanism on Mercury may have resulted in the transient production of anomalously high atmospheric pressures of short lifetime due to solar proximity.

Conclusions: Mercury has been largely resurfaced by effusive volcanism and here we present the first comprehensive estimates of the production function of these basalts and the associated outgassed volatiles. If Mercury's atmospheric loss rate was insufficient to lose all of the erupted gases, then it is possible that ancient, outgassed volatiles remain trapped in the planet's subsurface today. These outgassed volatiles are of a different composition from the H_2O ice observed at Mercury's poles today [e.g., 13], and thus the H_2O-ice deposits are better explained by an impact origin.

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