IONIAN PATERA VOLUMES AND IMPLICATIONS FOR FORMATION MECHANISM.
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Introduction: Volcanic caldera-like structures called *paterae* are a ubiquitous geomorphologic feature on the jovian satellite Io [1]. Paterae are the source of most of Io's volcanic thermal emission [2]. However, little work has been done to measure their depths and calculate their volumes of material removed [e.g., 3-7], a necessary quantity if the formation mechanism is to be understood. In addition to shadow measurements to estimate patera depth, recent work [8, 9] has created new stereo and photoclinometric products from *Voyager* and *Galileo* image data. We are using these products to systematically measure the depths and wall slopes of paterae across Io's surface. Paterae volumes are then calculated. As noted in [10] this work will allow the global characteristics of paterae to be studied, and formation models [6, 11, 12] can be tested, refined, or replaced.

Difficulties: There are many difficulties in processing spacecraft data of Io to extract the desired parameters due to the high radiation environment impacting the *Galileo* imaging system, uneven longitudinal and latitudinal coverage, and wide ranges of phase angles and spatial resolutions [13]. Additionally, the widely-differing albedos of surface units in and around numerous paterae make photoclinometry (PC) difficult, although assuming a patera shape and assigning albedo brightnesses to different units allows profiles to be constructed [6]. A description of PC methodology for deriving paterae topography is given in an attendant LPSC abstract by White and Schenk [9].

Methodology: We have so far examined 23 paterae (Table 1). In short, the examples in Table 1 are from low-Sun PC images that have corresponding high-Sun albedo images that are used to directly gauge the differences in shading at low and high Sun angles. These albedo images are generally of a similar resolution to the PC images, with the exception of that used to make the Haemus DEM (not included in Table 1), which is quite blurred (high Sun images are rare at the poles). Mean diameters have been calculated from a range of profiles taken across the paterae; patera areas are calculated using long and short diameters and by regarding patera shapes as either rectangular or elliptical. All slopes are measured from the slope maps that are created alongside the PC DEMs. A fuller description of the methodology used is given in [9] and [14]. Patera depths were also calculated from stereo products.

Mobilisation and removal of volatiles: Some high resolution observations by the *Galileo* SSI camera show slumping of material that appears to have slid off tilted crustal blocks, suggesting upper surface layers that are not as coherent as the bulk material comprising the mountains. Io's upper surface appears to consist of a mixture of sulphurous compounds and silicate material, both as pyroclastics and lava flows. If most paterae are formed by the repeated injection of silicates at the base of this relatively unconsolidated layer, the sulphurous material can be mobilized and excavated. Assuming an upper-crust ratio of 70% SO_2 to 30% S, we have calculated the minimum total volumes of silicates needed to form the paterae in our study through heat exchange between intrusion and overlying volatiles.

Results: Table 1 shows results for paterae depth, estimates of paterae volume and the energy needed to heat and melt the paterae volume of sulphur and SO_2. The evacuation of this material might form a patera by unroofing of the silicate intrusions that are the heat source [e.g., 7]. Table 1 also shows the volume of silicate magma that is needed to yield its heat to mobilise the sulphurous materials. The volume has been increased by 10% to account for the fact that part of the volatiles are replaced by the silicates themselves. The depth of the initial volatile layer appears shallower than it actually is because part of the patera has filled with silicates.

Conclusions:

1. Depths of 23 paterae determined using the nominal PC method average 1.1 km (± 0.4 km). With stereo, depths average 1.4 km ((± 0.4 km). Rough volume estimates (corrected removed volume) range from ~170 km^3 to ~7430 km^3.

2. The heat that has to be supplied to mobilise the sulphurous materials (heating them to melting point and then melting them – no further heating is so far included) comes from silicate (basalt) intrusions, and requires 8 $x10^{19}$ to 3 x 10^{21} J for the paterae in Table 1.

3. Initial estimates of *minimum* silicate volumes needed to mobilise the volumes of sulphurous material to form these paterae range from ~14 km^3 to ~640 km^3, likely supplied in a series of intrusive episodes.

4. Our results support the idea of a ubiquitous volatile rich layer on Io that is of order ~1 km thick.

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Table 1. Dimensions of paterae with estimates of heat needed to excavate the necessary volumes of volatiles

Name	Patera centre lat., °	Patera centre long., °W	PC nominal depth, km	Stereo nominal depth, km	Current volume of patera, km^3	Vol. of S removed[a], km^3	Vol. of SO_2 removed[a], km^3	Heat needed to melt S, J	Heat needed to melt SO_2, J	Total heat[b] needed to melt volatiles, J	Min. volume of basalt needed, km^3 [c]
Unnamed	-5.9	190.4	1.63	1.99	2027	1419	608	7.04E+20	2.29E+20	9.33E+20	192
Unnamed	-5.5	187.3	1.11	1.63	2461	1723	738	8.55E+20	2.78E+20	1.13E+21	233
Unnamed	-7.8	184.2	0.84	1.04	1741	1219	522	6.05E+20	1.96E+20	8.01E+20	165
Unnamed	6.2	188.0	0.70	1.64	751	526	225	2.61E+20	8.48E+19	3.46E+20	71
Unnamed	15.5	185.9	0.73	1.53	3330	2331	999	1.16E+21	3.76E+20	1.53E+21	315
Unnamed	-26.5	181.4	1.07	1.31	1659	1161	498	5.76E+20	1.87E+20	7.63E+20	157
Unnamed	-31.1	187.7	1.06	1.46	1548	1084	464	5.38E+20	1.75E+20	7.12E+20	147
Reiden P.	-13.1	235.3	1.31	1.59	3884	2719	1165	1.35E+21	4.38E+20	1.79E+21	368
Unnamed	-15.0	231.0	1.13	1.90	2145	1502	644	7.45E+20	2.42E+20	9.87E+20	203
Unnamed	-42.9	238.9	1.31	1.39	713	499	214	2.48E+20	8.05E+19	3.28E+20	67
Unnamed	-13.4	75.9	0.59	0.64 (PC) 0.57 (albedo)	164	115	49	5.70E+19	1.85E+19	7.55E+19	16
Unnamed	48.3	156.2	0.61	0.95	1688	1182	506	5.86E+20	1.91E+20	7.77E+20	160
Thomagata P.	25.2	165.8	1.30	2.28	1677	1174	503	5.82E+20	1.89E+20	7.72E+20	159
Reshef P.	27.3	157.9	1.26	1.38	2065	1446	620	7.17E+20	2.33E+20	9.50E+20	195
Chaac P.	12.0	157.5	1.13	1.47	6751	4726	2025	2.34E+21	7.62E+20	3.11E+21	639
Balder P.	11.2	155.9	1.05	1.10	843	590	253	2.93E+20	9.51E+19	3.88E+20	80
Hiruko P.	-64.7	328.3	1.30	1.36	5791	4054	1737	2.01E+21	6.54E+20	2.67E+21	548
Bochica P.	61.0	18.5	1.66	1.05	3678	2575	1103	1.28E+21	4.15E+20	1.69E+21	348
Inti P.	-67.9	346.7	1.02	1.16	4199	2939	1260	1.46E+21	4.74E+20	1.93E+21	397
Aramazd P.	-73.4	335.9	0.72	0.82	1746	1222	524	6.06E+20	1.97E+20	8.04E+20	165
Unnamed	9.7	125.5	0.48	1.30	152	106	46	5.28E+19	1.72E+19	7.00E+19	14
Unnamed	23.5	125.8	2.01	1.27	5279	3695	1584	1.83E+21	5.96E+20	2.43E+21	500
Shoshu P.	-19.5	323.9	1.30	1.75	2562	1793	769	8.90E+20	2.89E+20	1.18E+21	243

[a] Assumes upper-crust volatile abundances of 70% SO_2 and 30% S.
[b] Balances latent and specific heat loss from basalt magma with melting and heating of volatiles.
[c] The volume of silicates has been increased by 10% to allow for partial filling of the patera by the silicates themselves, i.e., the original depth of the volatile-rich layer is greater than currently indicated by depth measurements.