POWER OUTPUTS AND VOLUMETRIC ERUPTION RATES FOR IONIAN VOLCANOES FROM GALILEO-NIMS DATA.

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Introduction: Eruption volumetric flux (E) is probably the most important eruption parameter, as it determines the style of eruption (e.g., higher effusion rates produce channel-fed flows that are more voluminous and faster moving) and therefore the subsequent evolution of the thermal signature of the eruption. It is possible to estimate E from measurements of the thermal emission (Q_{tot}) from an active volcano [1,2,3]. For a number of Ionian volcano spectra (0.7 to 5.2 mic) obtained by Galileo-NIMS, the two-temperature (2T) model [4], produces the total thermal output for “hot” and “warm” components. From these, volumetric eruption rates are calculated. Additionally, the 2T fits also constrain minimum lava temperatures, of greater importance since the discovery of high-temperature (>1600K) ultramafic volcanism on Io [5]. The 2T model produced one of the first unambiguous determinations of silicate liquidus temperatures (>1100 K) on Io’s surface from Galileo data and has been used to chart the evolution of eruptions at Loki [6] and Pele and Pillan [3]. It has proved to be an excellent metric. Now, the 2T model has been fitted to all appropriate hot spot spectra in the G1INNSPEC01 observation [see 7,8]. The 2T fit is used where statistically justified (using the F-test of significant difference in variances): otherwise, a single temperature (1T) fit is used.

Model fits to NIMS data: The NIMS G1INNSPEC01 volcano data have been fitted with a 1T model [7]. A silicate cooling model (the Io Flow Model, or IFM) was used to determine rates of areal emplacement (7 to 80 m^2/s) and flow ages (typically days to months) [7]. Although the IFM produced excellent fits to these NIMS data over most of the wavelength range, with Prometheus, Zamama, Culann, Tupan, Monan and Amirani/Maui there was excess flux to the model fit at short wavelengths, caused by additional high-temperature areas. Statistically, adding a second IFM component was not justified with these data.

Applying the 2T model to these spectra produced better fits from those obtained using the 1T model. The 2T temperatures and areas are also a more realistic representation of the actual temperature and area distribution on a lava flow (a small, active hot area, and a large warm area, the crust on the flow).

Table 1 shows the 2T fit to the grating position spectrum yielding the largest thermal output (column 2) for each volcano, and the fit producing the highest hot component temperature (T_{hot}) (column 3). Temperatures are ± 10 K. Areas (A_{hot} and A_{warm}) are ± ~5%, and are corrected for emission angle. Q_{tot} values are given in Table 2, derived from the “maximum intensity” temperatures and areas. Also shown are thermal outputs derived using the IFM [8]. Data for Amirani and Maui are combined, as there is evidence that in the low-resolution observations the thermal emission attributed to Maui may be coming from distal Amirani flows. The “maximum intensity” grating position spectra for Hi’iaka, Sigurd, Gish Bar, Zal, Altjirra, Malik and Arinna Fluctus are fitted with the single-temperature model, which yield the maximum values of Q_{tot}.

Table 1. Temperatures and areas, 2T fit to G1INNSPEC01 data

	“Maximum intensity” spectra		Max. **temp**
Volcano	temp **T_{hot}**, K area A_{hot} km^2	temp **T_{warm}**, K area A_{warm} km^2	T_{hot} , K, T_{area} , km^2
Monan	**1007**, 0.191	**427**, 33.2	**1158**, 0.0401
Amirani	**1022**, 0.348	**420**, 173.1	**1207**, 0.0950
Maui	**1182**, 0.034	**471** 32.6	**1295**, 0.0187
Tupan	**974**, 0.270	**449**, 31.1	**1137**, 0.0808
Prometheus	**1263**, 0.052	**437**, 53.6	**1479**, 0.0274
Culann	**993**, 0.209	**424**, 69.2	**1230**, 0.0592
Zamama[4]	**1100**, 0.080	**450**, 53	n/a

Table 2. Power output: comparison of model fits

Volcano	2T model fit, Q_{tot}, GW	IFM fit, Q_{tot}, GW
Amirani	327	243
Maui	96	97
Amirani + Maui	423	340
Culann	139	93
Monan	85	73
Prometheus	118	86
Tupan	79	58
Zamama [4]	126	106

The “maximum intensity” T_{hot} values range from 974 K (Tupan) to 1263 K (Prometheus). These temperatures are typical of remotely obtained data of silicate eruptions. T_{warm} values range from 420 K (Amirani) to 471 K (Maui). The T_{hot} maximum values obtained from fitting all grating position spectra range from 1130 K (Tupan) to 1479 K (Prometheus).

The maximum T_{hot} values are mostly in the typical temperature range for basaltic compositions, even allowing for some cooling. Prometheus is borderline. Given the relatively low-energy emplacement style at these locations [8] it is unlikely that hotter components at ultramafic temperatures, if present, could be detected in these NIMS data. It is noted that Q_{tot} (as determined using the 2T model) is in most cases slightly larger than that determined using the IFM, with the bulk of the additional emission beyond the NIMS wavelength range. This highlights the importance of longer-wavelength data (> 5 micron) to constrain model fit and determination of Q_{tot}.

Calculating E: It is possible to estimate eruption volumetric flux E (m^3/s) from volcanic thermal emission using [2]:

$$E = Q_{active} / \rho_{lava} (c_p \Delta T_{liq\text{-}stop} + L \Delta c_f) \quad (1)$$

where Q_{active} is the total thermal flux from the active part of a flow; ρ_{lava} is lava density; c_p is specific heat capacity; $\Delta T_{liq\text{-}stop}$ is the temperature range from liquidus temperature to the temperature where the flow comes to a halt, L is the silicate latent heat of fusion, and Δc_f is the change in crystallization fraction over ΔT. Values for basalt are typically as follows: ρ_{lava} = 2600 kg/m^3; c_p = 1500 J/kg/s; L = 3 x 10^5 J/kg; and $\Delta T_{liq\text{-}stop}$ = 1475 – 1073 K and Δc_f = 0.0325 [x]. For ultramafic compositions, ρ_{lava} = 2800 kg/m^3; c_p = 1200 J/kg/s; $\Delta T_{liq\text{-}stop}$ = 1900 – 1073 K; and L = 8 x 10^5 J/kg. Determining Q_{active} is often problematic even on Earth and therefore more difficult on Io. The NIMS data contain thermal emission not only from the active parts of the flow but also from old, cool flow units. It is not possible to determine how much of Q_{tot} is Q_{active} especially when the entire flow, including all active and inactive areas, is sub-pixel so Eqn. 1 has to be modified to include heat from the older parts of the flow that have cooled to T_{warm}, thereby utilizing the *total* volcanic flux. E values are shown in Table 3 for both basaltic and ultramafic compositions. Mass fluxes are calculated by multiplying E by ρ_{lava}.

Results: The basalt E values derived here generally compare well with the values determined using the IFM (basalt), which is almost surprising when it is remembered that the IFM E values are derived using an average flow thickness derived from the global Io volcanic flux. The biggest difference is at Altjirra, caused by a lack of IFM and 2T constraint at longer wavelengths. Ultramafic E rates are lower than those for basalt. This is because greater specific and latent heats per kg are released as ultramafic flows cool and solidify. These eruption rates can be compared with other eruptions on Io. One of the best observed large Io eruptions was the highly vigorous Pillan 1997 eruption, which had a Q_{tot} of 3610 GW and an E of 3300 m^3/s during June 1997 [3,9]. Eqn. 1 yields an E of 3160 m^3/s. Subsequent measurements of Q_{tot} and estimates of Δc_f are being used to determine Pillan E values as a function of time. The large ratio of warm to hot area is indicative of a relatively quiescent, non-turbulent style of emplacement, with no fire-fountaining.

Table 3: Volumetric eruption rates

	E, using Q_{tot} m^3/s		E, IFM [8] m^3/s
2T fit	*basalt*	*ultramafic*	*basalt*
Amirani	66.8	42.1	79
Maui	20.3	12.5	27
Amirani+Maui	87.1	54.6	106
Monan	17.6	11.0	41
Tupan	16.5	10.3	45
Prometheus	24.3	15.3	35
Culann	28.4	17.9	38
Zamama	26.9	16.6	51
1T fit	*basalt*	*ultramafic*	*basalt*
Hi'iaka	25.0	14.2	20
Sigurd	17.1	9.8	12
Gish Bar	12.7	7.2	12
Zal	24.2	13.6	28
Altjirra	73.5	43.1	21
Malik	12.3	6.6	7
Arinna Fluctus	10.7	6.1	7

A comparison of interpretations of low-resolution data of volcanism on Io and Earth [10] shows that for a given eruption style terrestrial E rates are generally much smaller than those seen on Io. Additionally, in spite of hotter magmas and larger eruption rates, ionian thermal fluxes per unit area are similar to those on Earth for a given eruption style.

Acknowledgements: This work was carried out at the Jet Propulsion Laboratory-California Institute of Technology under contract to NASA. This work was funded by NASA JSDAP grant 624-02-00-18. AGD thanks Dave Pieri for useful discussions of determining E.

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