INTERPRETING LOW SPATIAL RESOLUTION THERMAL DATA FROM ACTIVE VOLCANOES ON IO AND THE EARTH.

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Introduction: Monitoring of remote terrestrial volcanoes via orbiting platforms has recently become much more routine by taking advantage of existing weather satellites as well as the new EOS spacecraft [1,2]. These terrestrial satellite data have been used to detect the onset of eruptions [3,4] as well as to monitor parameters such as effusion rate during the eruption [1]. However, the interpretation of the style of volcanism has generally been attempted only when high spatial resolution (or ground-truth) data were also available [e.g., 1,3,5]. Improving our ability to interpret the high temporal resolution but low spatial resolution data is an important goal.

Recent data from Jupiter's moon Io provides an unusual opportunity to independently assess our ability to interpret remote sensing data from active volcanoes. The bulk of the data from Io has had low spatial resolution, moderate spectral. The data also span over 2 decades, albeit with spotty temporal coverage [6-8]. There is sufficient similarity in the terrestrial and Ionian data sets to allow the same qualitative interpretive techniques to be applied to both bodies.

Io Data: The monitoring of Io's thermal activity includes a semi-continuous Earth-based observation campaign since the late 1970's, flybys by the two Voyager spacecraft in 1979 and Cassini in 2000, and the Galileo spacecraft in orbit around Jupiter since 1995. The most advanced ground-based observations and HST provide ~1000 km/pixel IR imaging of hot spots on Io. However, during occultations, hot spots can be located to within tens of kilometers in longitude [6]. Thermal data from Galileo comes mostly from the NIMS instrument which covers 0.7-5.2 µm with up to 408 spectral bands [7]. The SSI camera has provided emission data from the visible and shortest infrared form images taken while Io was in eclipse [8]. The ISS camera onboard Cassini has recently provided very high temporal resolution data of Io in eclipse in the visible and shortest IR [9].

Interpreting Ionian Volcanism: Close to 100 active hot spots have been identified on Io to date [7]. Many of these have been monitored for years and several have been examined in detail using high resolution data from the recent Galileo flybys of Io. The style of activity at these volcanic centers had been speculatively identified using the earlier low resolution data (see Table 1).

Table 1: Criteria for Interpreting Thermal Emissions from Active Volcanism on Io and the Earth.

Style of volcanic activity	*Characteristics*
Lava Lake	Long-lived, small, geographically fixed hot spot with high/medium average surface temperature and minimal temporal variations.
Lava Fountains	Short lived, medium size, fixed hot spot with high average surface temperature and rapid decay in intensity.
Open Channel or Sheet Flows	Short-lived, large hot spot that grows in size with medium to high average surface temperature that gradually decays.
Insulated (Tube-Fed) Flow Field	Long-lived, wandering hot spot with low average surface temperature.

In several cases, predictions made using these criteria have been successfully confirmed by the new data. The steady high temperature signal from Pele was interpreted to be a lava lake. 14-17 m/pixel images of Pele in the dark show a series of glowing spots that coincide with the margins of an active lava lake. Amirani and Prometheus were interpreted to be compound pahoehoe flow fields fed by long-lived, moderate effusion rate eruptions. Their plumes and most prominent hot spots had shifted ~100 km between the Voyager and Galileo observations. High resolution (~20 m/pixel) images of the Prometheus flow field show a convoluted flow margin consistent with pahoehoe flows. Comparison of ~100 m/pixel images of both flow fields obtained in orbits I24 and I27 allows for a quantitative estimate of the coverage rate of the flows and confirms the compound nature of both flow fields. The observed areal coverage rates are remarkably similar to those estimated from unresolved thermal data [10]. Galileo also had the good fortune to capture the beginning of a short-lived thermal outburst. These had been previously interpreted to be lava fountains erupting from fissure vents [11]. The fortuitous high resolution observations showed that the hot material was indeed a curtain of lava. Thus all our major interpretations of low resolution thermal data turned out to be correct. Some more quantitative results are listed in Table 2.

Table 2. Thermal characteristics of Some Ionian Volcanoes.

Center	**Eruptive Style**	**Thermal Characteristics**
Pele	Lava lake	Steady, fixed emission of 210-280 GW (~15kW/m^2)
Pillan	Open channel flows	Dropped from 3600 GW to 350 GW as hot area decreased from 30 to 0.5 km^2
Prometheus	Insulated flow field	Steady emission of ~100 GW (~2kW/m^2), moved ~80 km in ~20 years.
Amirani	Insulated flow field	Steady emission of ~300 GW (~2kW/m^2), multiple centers of activity, some shifted ~100 km.

Terrestrial Data: For monitoring the style of eruption, the most useful remote sensing data come from weather satellites. This is because the timescales of interest for changes in the style of volcanic activity and the weather are similar (<hours). The NOAA GOES and AVHRR satellites have provided much useful information already. GOES satellites are geostationary and image a hemisphere every 15 minutes at ~4 km/pixel in 5 spectral bands between 0.5 and 12.5 microns. AVHRR instruments are carried on polar orbiting spacecraft with 2 passes per day per spacecraft at the equator and more frequent coverage near the poles. AVHRR provides >1 km/pixel images in 5 bands across 0.5-12.5 microns. Table 3 shows some AVHRR data on some terrestrial volcanic eruptions with known styles of eruption. To date, the GOES data have been used to determine the timing of different volcanic events during an eruption [3,4] while the AVHRR data have been used to identify the types of active volcanic features at several volcanoes [1

Table 3. Thermal Characteristics of Some Terrestrial Volcanoes.

Volcano	**Eruptive Style**	**Thermal Characteristics**
Erebus	Lava lake	Steady 0.05-0.1 GW (1-6 kW/m^2)
1992 Etna	Open channel and tube-fed aa flows	Peak at 7.3 GW, drop to 0.5 GW (1.2-3.5 kW/m^2) while the hot area varied between 3.7 and 0.1 km^2
1991 Kilauea	Tube-fed pahoehoe	0.3-0.7 GW (0.1-0.05 kW/m^2)
1984 Krafla	Lava curtains and open sheet flows	26-50 GW (~0.5-1.5 kW/m^2)

Other satellite data that have been used in geologic studies (e.g., LANDSAT and ASTER) have much greater spatial and spectral resolution. However, they typically can image an area only about twice a month and require extensive advance planning in order for an observation to be acquired of a specific target volcano. As such, they are less useful for routine monitoring of unexpected volcanic activity. MODIS, with a 1-2 day repeat and 0.25-1 km/pixel resolution in 36 bands is a cross between these two types of data.

Comparisons: While there are a great many similarities in the data sets available from the Earth and Io, there are also some important differences. In particular, the temporal resolution of the Io data is generally only on the order of months, while data is available at 15 minute intervals on the Earth. Somewhat disheartening is the fact that the terrestrial data generally has much poorer spectral resolution. This hinders the direct terrestrial application of some of the specific quantitative techniques applied to Io.

However, using the same simple criteria we applied to Io, it is possible to properly interpret the low spatial and spectral resolution thermal data from lava flows at Kilauea and Mt. Etna, the lava lake at Mt. Erebus, and lava fountains at Krafla. The fact that the same criteria function for terrestrial and Ionian data indicates that these common sense interpretations are very robust and can be assigned a high degree of confidence.

However, when we look at the quantitative results , it is immediately obvious that Io and the Earth are not the same. The Ionian activity is generally much more voluminous and involves hotter lavas, leading to much larger total thermal fluxes. Interestingly, for a given style of volcanic activity, the thermal flux per unit area is not entirely dissimilar between the bodies. Also, the lava effusion rates estimated from both bodies have been remarkably close to those estimated by direct measurement of the area covered by fresh lava. This again suggests that the techniques we have developed to interpret thermal data from both the Earth and Io are surprisingly robust and trustworthy.

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