HEAT FLUX MONITORING OF STEAM HEATED GROUNDS ON TWO ACTIVE VOLCANOES
I.S. Diliberto, E. Gagliano Candela, M. Longo
Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Palermo, Italy

Introduction. The output temperature of Fumarole fluids is strongly related to the upward flux of magmatic volatiles. Some previous works, dealing with long term monitoring data, showed that the thermal anomalies associated to fumaroles output are strictly related to transients occurring in the volcanogenic vapor, responding to changes either of seismic and/or volcanic activity (Diliberto, 2013; Madonia et al., 2013a, 2013b; Cannata et al., 2012; Milluzzo et al., 2010; Aubert et al., 2008).

Some examples of heat flux monitoring from two very different volcanic areas, showed in figure 1 (Vulcano Island, Mount Etna) are presented here, and the results are compared to other observational data.

The monitoring method here applied, worked properly to follow time variations of surface heat flux in particular field conditions, where a simplified equation can be applied to the surface heat balance. The key parameter for this simple and cheap monitoring method is the temperature gradient in the ground, measured on the main heat flow direction in an area where an active fracture network is interested by steam up-flow. In a porous ground profile, the temperature gradient allows to properly evaluate the time variations of heat flux within the range of about 30-300 w · m⁻² (Aubert et al., 1999), but the main conditions are that, within the monitored soil profile, the radiative and convective components of the heat transfers can be considered null.

The discussed datasets widely demonstrated the direct link between temperature anomalies monitored on surface and transient state changes of the volcanic system, confirmed on a multidisciplinary basis. The presented data came from a close conduit volcano (La Fossa active cone, Aeolian Islands) during a quiescent period (since 1990, but particularly in 2004-2007); but also from an active erupting volcano, that is Mount Etna, during the eruptive cycle which produced the New South East Cone (2009 to 2012). Results about temperature monitoring on Vulcano island are shown in Figs. 2b, 2c, 2d. Results about temperature monitoring carried out on M.t Etna are shown in Figs. 3b, 3c, 3d.

Methods and sites descriptions. Soil temperatures were acquired hourly at four depths on a short vertical profile into the ground, by automated stations, based on Onset Microstation four-channel data loggers, each connected to two 12-bit digital temperature smart sensors from the
Fig. 1 – Maps of the studied areas with the location of the sites cited in the text: a) Mount Etna volcano; TBL - Monitoring site in the steam heated soil on the northern flank, FBT - low temperature fumaroles. In the left corner the Southern Mediterranean region and the position of mount Etna (white square); b) Sketch map of Vulcano island showing the location of the seismic stations and tiltmeter. In the inset at the upper right corner the location of the monitoring sites of CO$_2$, fumarole temperature and soil temperature is reported (from Milluzzo et al., 2010).

Island of Vulcano - Multiparameter comparison

Fig. 2 – a) Locations of the monitoring stations of Vulcano island and recorded change of temperature both in high temperature fumaroles fumaroles (b) in the ground profile (c). The red curve in Figs. 2a and 2b show the variable rate of volcano-seismic release during the monitoring period. d) CO$_2$ content in the fumarole samples.
same manufacturer. Sensors operate in the range −40 °C to 100 °C, with a resolution of 0.03 °C and an accuracy of ±0.2 °C. Temperatures were measured every 4 min and their hourly averages were stored in the permanent memory of the logger.

The two selected sites are the top of the Bottoniera line craters in the Mt. Etna, and the middle rim of the cone of La Fossa Vulcano Island. The monitored data were compared to meteorological parameters (rainfall, barometric pressure, air temperature) from local weather stations. The theoretical bases and the simplified heat balance applied to calculate the heat flux from the monitored data have been described in Aubert (1999) and Aubert et al. (2008).

**Results.** For the Vulcano island case study (Fig. 2) the time variations of different data-series were compared in near real time, since the multidisciplinary approach to some evidences came by the direct collaboration with other groups of researchers actively involved in the geophysical monitoring of this quiescent system (Cannata et al., 2012; Madonia et al., 2013; Milluzzo et al., 2010).

During periods of higher thermal release, the main fumaroles emissions always showed anomalous contents of magmatic gases (see for example the CO₂ content in graph d) as highlighted by the periodical sampling of fumaroles release systematically carried out. Moreover the rate of volcano-seismic release during the monitoring period increased in the same periods. See for example the red curve in Figs. 2a and 2b (from Diliberto, 2013).

**Mount Etna volcano heat flux monitoring of Steam Heated Soil**

![Image](image_url)

Fig. 3 – a) Image from the WEB showing an instance of the recent eruption, with the TBL monitoring station on the opposite flank with respect to the direction of last falls and flows emitted by the New South East Crater. b) Heat flux variations (validated data) in the steam heated soil; cumulated volume of erupted material (red triangles, values on the right axis); monthly averages of air temperature at the closest weather station (Blue curve, values on the right axis.). c) Total Radiant Energy (T RE, scale on the right axis) retrieved for lava fountain episodes and strombolian explosions occurred at the New South East Crater (data from Bombrum et al., 2016); Surface Heat flux calculated at BTL monitoring station (HF Daily averages, scale on the left axis). d) IR image of the exposed surface around the monitoring stations, showing the actual temperature range.
For the Mount Etna case study (Fig. 3), we waited for the scientific publications about this eruptive period, in order to get new parameters related to the eruptive activity. The scientific production about an eruptive volcano is faster, so in a few years we could gather some multidisciplinary data (for example Bombrum et al., 2016; Bonaccorso and Calvari, 2013; Bencke et al., 2013), independently acquired, well interpreted, revised and then widely accepted by the scientific community.

Fig. 3a shows the position of our monitoring station (TBL), on the opposite flank with respect to the direction of last pyroclastic falls and flows emitted by the New South East Crater, 4 km to South. The exposed ground surface actually shows a wide temperature range, as shown in the IR image taken in September 2016, during a cloudy day with rainfall (18-41 °C).

During the monitoring period (September 2009-2012) the surface heat flux from the ground registered changes directly related to the volcanic activity and no delay has been observed between the changes of eruptive rate and the relative change of surface heat flux (Fig. 2b). The monitoring site, located on the opposite flank, was about 4 km away from the new eruptive center, located on the SE flank. In 2010, few months after a seismic swarm at the pernicana fault, a new eruptive cycle started at SE crater and a new cone formed. The new vent, named “New SE Crater” was already 240 m high in spring 2013. Magma rising in new conduits keep its gases up to the surface and eruption of this period were more explosive than before. In Fig. 2b the white arrows (1-4) indicate the ranges represented by the mean term variations of heat flux during the pre-eruptive phase (1); during low emission rate (2), high emission rate (3) periods, and the after the eruptive period (4).

In Fig. 3c the distal heat flux from the ground (HFD) show an inverse relationship with the Total Radiant Energy (TRE, scale on the right axis) retrieved for lava fountain episodes and strombolian explosions at the New South East Crater (data from Bombrum et al., 2016). Moreover, in the same figure, the continuous heat release monitored in distal position (HFD) showed in the short term (±1 day) around the explosive activity interesting correlations with the Radiant Energy evaluated by Bombrun et al. (2016) by analyses of IR imaging.

The different datasets under consideration showed that, in case of stress-induced changes in the vapor pressures, the meteorological noise has a negligible effect and the time variations of heat release from fumaroles areas; The heat flux from the ground has been related to many other geophysical parameters, such as deformations, seismic release, or increase of magmatic component in the fluid release. On the contrary, the local heat flux from soil resulted essentially modulated by external variations (like sun radiation, rainfall, atmospheric pressure) during phases of stationary convection, when the steady state pressure field appeared less perturbed by volcano-tectonic activity.

Starting from these monitoring evidences, the fumaroles areas should be considered as indicators of geodynamic instability, and the implementation of multidisciplinary observation systems by a new network of monitoring stations able to highlight the main variations of surface heat flux by these particular observational sites, and their surroundings, would be convenient. By adding the geochemical perspective to a well established geophysical monitoring network we could successfully address the interpretation of observed phenomena and a timely evaluation of volcanic hazard.

A volcano, as well as geothermal area, are characterized by a thermal transients higher than the surroundings. In these areas the fluid circulation is a form of work easily to monitor in continuous, as the expression of extensive and widely diffuse energy flux toward the earth surface, even if the intensity is lower than those associated to the episodic paroxysms characterizing the main eruptive vents. The right perspective for interpreting all the observational data could came comparing dataset acquired on a very long term period at an adequate sampling rate, to avoid wrong interpolations of time-series. Interpretation can be correctly addressed only in the framework of a multidisciplinary observation system, keeping in mind that the preparatory stages of earthquakes and volcanic eruptions/unrests are deeply linked by mutual cause-
effect relationships. Both geophysical and geochemical anomalies are then complementary expressions of a general disequilibrium in the local geodynamic state. Both perturbations in the pressure state variable, or in the temperature distribution of the deep system, result in an excited state and produces heat and mass flows towards the surface of the multiphase system under investigation. What we suggest is to do the temperature monitoring of some selected sites and to merge the observed variations to comparable time series of different parameters from our geochemical subsystem (hydrogeological, atmospheric and geological data).

**Conclusions.** Through an empirical approach we have compared different time series of data, in order to highlight surface variations related to the energy released by a buried system. The surface heat fluxes, derived by monitoring temperature profiles, are original data from these authors, and results were validated and verified by experimental procedures during a previous research project, partially funded by the National Department of Civil Protection. The other data considered for comparison came from the tables included in scientific papers, they were validated and accepted by editors, among the big amount of data acquired to follow and model Mt. Etna and the Aeolian Islands behavior. In conclusion, continuous monitoring of surface temperature makes it possible to follow with a high temporal resolution, and in real time, all of the episodic increases in pore pressure that occur in geothermal and volcanic systems. Further improvements in multiple-parameter approaches are necessary to reveal the mechanism underlying these variations, since heat and fluid release can be influenced not only by the change in input from magmatic sources but also by the geodynamic instability of the area.

**References**


