Bulletin of Volcanology (2024) 86:30
https://doi.org/10.1007/s00445-024-01720-0

DATA REPORT

Temperatures recorded from January 2019 to February 2023 in the high-temperature fumaroles of the active cone of La Fossa Caldera

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Received: 8 May 2023 / Accepted: 19 February 2024

Introduction

Outlet temperatures are measured every hour in the high-temperature fumaroles (hereafter HTF) located in the summit area of La Fossa cone, and transmitted once a day to the remote observatory. On the Island of Vulcano (Italy), the HTF stations are a part of the comprehensive geochemical and geophysical surveillance network including seismic signals, ground deformation, and some selected parameters related to hydrothermal activity. Along with the environmental parameters used to evaluate the external effects, the other continuous monitoring data-series directly related to the gas release are the SO_2 flux from the main fumaroles, the CO_2 flux from soil, and the chemo-physical parameters of groundwater (like the water temperature, conductivity, total pressure of dissolved gases, and the water level).

The INGV surveillance network, detecting different geochemical and geophysical signals (e.g., Alparone et al. 2010; Inguaggiato et al. 2018; Stissi et al. 2023), allows us to examine the surface effects of processes originated at depth, and detect how the different datasets can be time-related (e.g., Cannata et al. 2012; Federico et al. 2023). The HTF temperature records always showed a medium-term period (from weeks to several months) of increasing heat flow heralding any unrest, before the abrupt and intense degassing that marks the onset of the critical behavior of La Fossa Caldera. The last impulsive onset occurred in 2021, and in early November, we registered the acme of the exhaling crisis. The strong increase in the vapor output from the fracture system feeding both the thermal groundwater and crater fumaroles caused the steep increase of the HTF outlet temperature, and the associated appearance of anomalous increase in soil CO_2 flux, soil heat flux, and plume SO_2 flux (Federico et al. 2023). All the anomalous monitoring parameters, quantified during the unrests by the INGV surveillance network, were interpreted as combined effects of episodes of increasing degassing from a steady-state magma body (Granieri et al. 2006). During any previous unrest, the very first signals detected by the multi-parameter monitoring network of stations operated by the INGV were the increases in outlet temperatures and steam output from fumaroles (Italiano et al. 1998; Paonita et al. 2013; Diliberto 2021), correlated to an enhanced concentration of acidic gas species. Moreover, we observed an episodic increase in the exhaling area during all those degassing crises, although it was rarely quantified in a repetitive mode (e.g., Bukumirovic et al. 1997; Diliberto et al. 2022; Pailot-Bonnétat et al. 2023). The episodes of unrest have been generally accompanied by an increase in the seismo-volcanic events with negligible ground deformation (e.g., Chiodini et al. 1992; Alparone et al. 2010). Many authors excluded the hypothesis of a correlated magma migration, but episodic fluid migration and cyclic water to vapor transformations through shallow depths (less than 1000 m) were suggested by electric and gravimetric studies (Berrino 2000; Di Maio and Berrino 2016). This last unrest ground deformation data (GNSS and tilt systems) showed inflation of the active cone, interpreted as due to the vapor expansion, just between September and November 2021 (Federico et al. 2023).

The high-temperature fumarole (HTF) monitoring network

The outlet temperatures of a few HTF vents located at Vulcano, in the summit area of the La Fossa cone, have been monitored continuously by INGV-PA since June 1984. This

Editorial responsibility: C. Widiwijayanti

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monitoring activity is carried out as part of the joint INGV-Civil Defense program. Inguaggiato et al. (2018) published details about the present methods of data collection; moreover, Diliberto (2013, 2017, 2021) published some examples of time series analysis to the same thermal data. A prolonged phase of tests has accompanied the birth of the present system of acquisition and data transmission, due to the harsh environmental conditions and absence of electric energy supply in the field. Continuous upgrades and improvements of both technologies and materials used are required. The corrosive acidic gases, high moisture, and high temperatures require constant maintenance of the network (twice a year, on average) with frequent substitutions of spare parts, including the thermal probes (chromel–alumel thermocouples type K, measurement interval from − 200 to + 1200 °C), temperature transmitter (4–20 mA, model 300TX, RS code 185–2363), wire, data-logger, electronic components, solar panel, batteries, etc. The continuous analog signal produced by the thermocouple is converted in voltage by a shunt (precision resistance 0.1%) and reaches the 16 bit A/D converter (model A/D 7715). The system accuracy results from the addition of single accuracies (probe + device) and the final resolution of the temperature measurement is about ± 0.3 °C. Data are acquired in situ at fixed intervals of time; automatic polling and transmissions to the local server at INGV-Pa are scheduled once a day, by a mixed system (UHF radio + GSM data). The data-logger can be remotely programmed, downloaded, and also reconfigured. The present configuration of the HTF network is shown in Fig. 1c (TK1, TK2, TK3, TIS; Fig. 1c). The metadata containing positioning information and equipment relating to each individual site are contained in the "thermal station" supplement. The site location of the sensors depended on the information obtained by the fumarole fluids periodically sampled for geochemical determinations (data available on request at INGV-PA). We give here the name of the reference fumaroles (F5, F5AT, FA) to help readers find geochemical references to compare. To ensure the continuity of the long-term monitoring, we have not moved the site locations, although the fumarole vents have changed in extension, position, and intensity of emissions, during the long observation period, especially along the inner slope (IS zone in Fig. 1). On the upper rim of the HTF zone, the fumarole vent F5AT hosts two sensors (TK1-TK2) and the fumarole vent F5 hosts TK3. In the 2004 monitoring, we added the site TIS to the HTF network, whereas some site locations have been abandoned (namely F21 in Fig. 1c, and other low-temperature fumaroles). Actually, TIS is a low-temperature fumarole vent and it is located to the west of Fa fumarole, at a distance of 20 m from the high-temperature vent, which is periodically sampled for the chemical and isotopic determinations (data available on request at INGV-PA). Usually, we programmed the measurement interval window of 1 h. The acquired data showed the combined effects

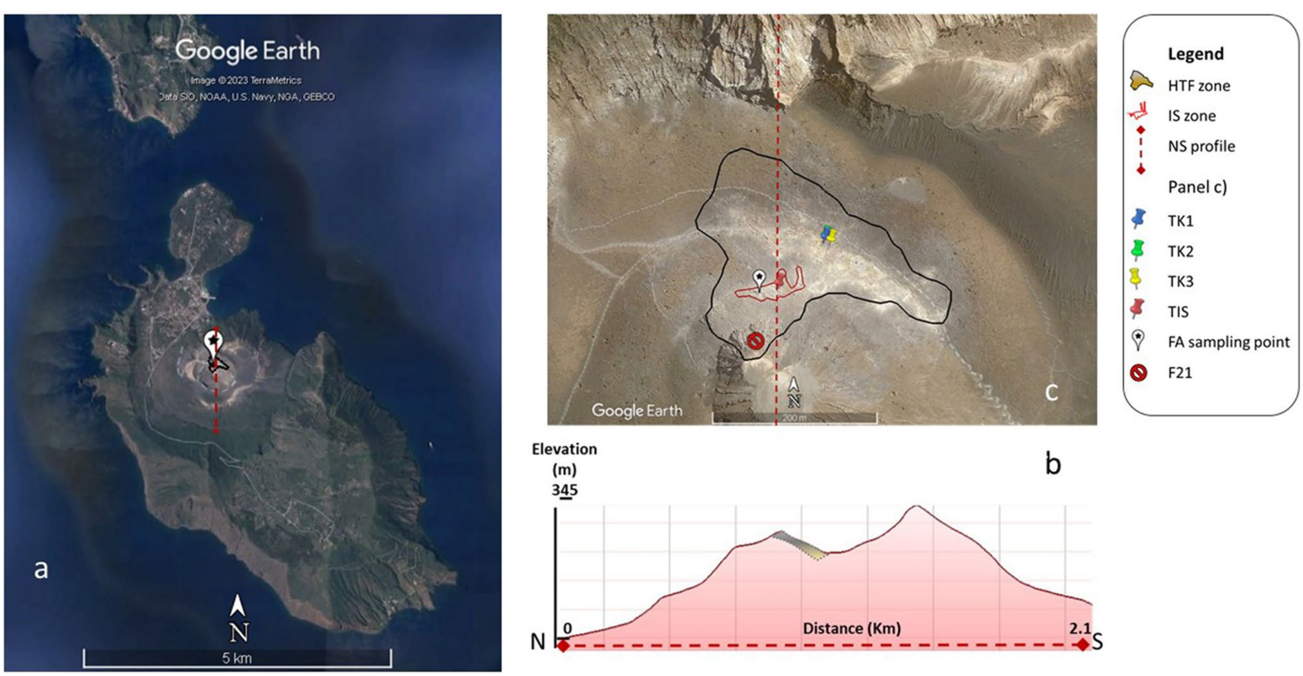

Fig. 1 **a** The Island of Vulcano with the HTF zone on top of La Fossa Cone. **b** The N-S profile passing through the main subaerial fumaroles. **c** Satellite image of the active cone of La Fossa, with the site locations of the HTF network (TK1, TK2, TK3; TIS)

of the external agents on the fumarole output (barometric changes, rainfall events, gusts of wind). On some occasions, we could remotely reduce the sampling window to a few minutes, to closely observing the effects of exogenous transients on thermal signals. We pay attention to the most intensive variations of thermal signals, expressed by temperature changes in the order of tenth degrees and lasting from many weeks to years, whereas we usually neglect the other thermal variations, essentially related to shorter term events and/or disturbances of external origin with respect to the hydrothermal system.

Presentation of the data

This Data Report includes all the validated data registered by the HTF temperature network from 2019 to February 2023. In 40 years, the monitored sites showed a general negative trend, a main cyclic modulation in the fumaroles located on the upper rim, and some episodic increases that are directly related to increased gas flux from the hydrothermal and/or the magmatic source (Diliberto 2021). Other previous unrest and short-lasting changes of fumarole temperature were recorded, sometimes related to a seismic swarm (e.g., Diliberto 2017; 2013; Cannata et al. 2012). In some cases, the additional effects registered in other stations suggested that the deep source disperses excess mass and energy out of the fumarole conduits, affecting the entire hydrothermal system to the base of La Fossa cone with transient conditions (e.g., Capasso et al. 1999; Federico et al. 2023). In other cases, like in 1998 or 2004, the central conduits feeding the HTF fumaroles were able to readily oust the new input of both mass and enthalpy, so the peripheral stations located at the base of La Fossa cone did not register anomalous signals (e.g., Diliberto 2011, 2013; Aubert et al. 2008).

The extension of the ground surface heated by the advection of high enthalpy fluids has greatly changed since 1984, and every monitoring site has shown its own range of temperatures and different local effects, due to different combinations of many processes, such as weathering processes, fracturing events, variable flows, and the unstable chemical composition of hydrothermal fluids. Temperature monitoring showed that the maximum-temperature fumarole moved from the inner slope (1991–1993, sites TIS and F21, Fig. 1) to the upper rim and along it (in 1996 sites TK1-2, in 2015 site TK3, Fig. 1). Moreover, the thermal area in the inner slope (IS zone in Fig. 1), including the FA sampling point, has increased progressively from about 230 m^2 (in June) to more than 2400 m^2, measured in May 1995 by Bukumirovic et al. (1997). During the following years, some other pulsations in the extension of the thermal anomalies have been observed, but not measured. After the unrest, the difference of temperature among TK1, TK2, and TK3 has decreased, and the reference fumaroles (F5, F5AT) show the same general behavior.

In Fig. 2, we report the annual temperature modes from 2013 to 2022, extracted from the hourly record of HTF data-series, in order to highlight the general trends of temperature at any monitored site. The annual modes are quite similar to the annual averages, but they show the general tendency of the monitored sites, filtering out any medium-term (a few months and several weeks) and shorter-term modulation (a few days and hours), without manipulating the original measured data. The general decreasing trends observed from 2013 to 2021 on the upper rim showed some smoothed inflections in 2018 and 2019, and a relevant inversion in 2022 (Fig. 2). Figure 3 shows the time series of raw

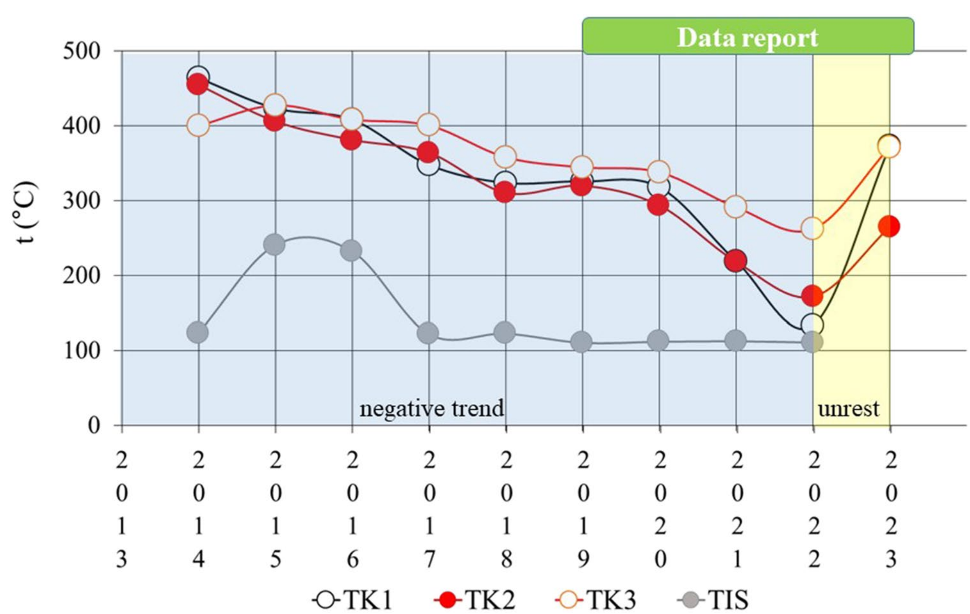

Fig. 2 Annual temperature (t, °C) modes extracted by the HTF data-series hourly recorded on Vulcano Island, from 2013 to 2022. The light blue and yellow backgrounds show the decreasing thermal release and unrest periods, respectively

temperature data, hourly recorded from 2019 to March 2023 and submitted to this Data Report. The hourly record shows detailed information about the timing of unrest. Rising temperatures suggest, for example, an anticipation of the unrest observed at the end of September (Fig. 3). In February 2021, the maximum outlet temperature reached the lowest value ever recorded over the whole fumarole field (TK3 was around 262 °C); Afterward, the temperatures reached the new maximum value in March 2022 (TK1 and TK3, around 384 °C), showing a total increase of more than 120 °C referred to the temperature recorded before the unrest. The thermal anomaly associated with the HTF began increasing, both in intensity and in extension, although the low-temperature fumaroles (LTF) have shown a constant temperature around 110 °C (e.g., TIS in Figs. 1, 2, and 3).

After seven years of a general low level of thermal activity and a decreasing trend of outlet temperatures, the fumaroles located on the upper rim begun increasing (monitoring sites TK1, TK2, and TK3, Figs. 2 and 3), during 2021. Differently, on the inner slope, the output temperature (TIS, Fig. 1) has generally shown a reference temperature around 110 °C, for more than 6 years (Figs. 2 and 3). During the last unrest, the increased flux of hydrothermal gases (mainly CO_2, SO_2, H_2S) has altered the air composition in proximity of the fumarole field, while the highest steam release has reduced the visibility on the inner slope. These new worst environmental conditions inhibited the access to the inner slope; thus, the acquisition of temperature at TIS has been missing after the last failure episode (occurred in June 2022), because we stopped the necessary maintenance procedures.

The new phase of unrest of the hydrothermal system becomes manifest at the end of September 2021, whereas the inversion of the last temperature trends was observed in January 2021, that is, about 8 months earlier. The unrest was characterized by an increasing rate of thermal and gas release (Inguaggiato et al. 2022a, b) associated to the onset of seismicity and deformation (Federico et al. 2023; Pailot-Bonnétat et al. 2023). The previous crisis on the Island of Vulcano, showing similar signs of hydrothermal unrest both for duration and intensity, dates back to 1996 (Diliberto et al. 2002; Capasso et al. 1999). Also in that case, the geochemical anomalies started to be observed in the fumarole vents located in the HTF zone (as an increasing flux of magmatic components and increasing outlet temperatures); thereafter, the anomalous release extended to the areas located at the base of the cone, showing increase of diffuse gas emissions, and anomalous variations in the thermal wells. From a thermal point of view, both unrests started during a negative trend of HTF temperatures and showed similar starting rates. The ground-based thermal parameters closely reflected the sequence of effects related to the last exhaling crisis. We tracked the evolution from a background hydrothermal release (e.g., in 2020) to the new higher thermal level (in 2022–2023), passing through the onset of unrest (in late summer 2021); finally, a general negative trend suggested the end of unrest (Fig. 3, waning period). The Fig. 3 shows different background colors corresponding to four evolution phases highlighted by hourly measurements: The outlet temperature of fumaroles is highly site-sensitive, and few monitoring sites cannot cover the total extension of the thermal anomaly, especially on such a dynamic system like La Fossa Caldera. However, the periodic measurements on different fumarole vents confirmed that the site locations of the HTF network still

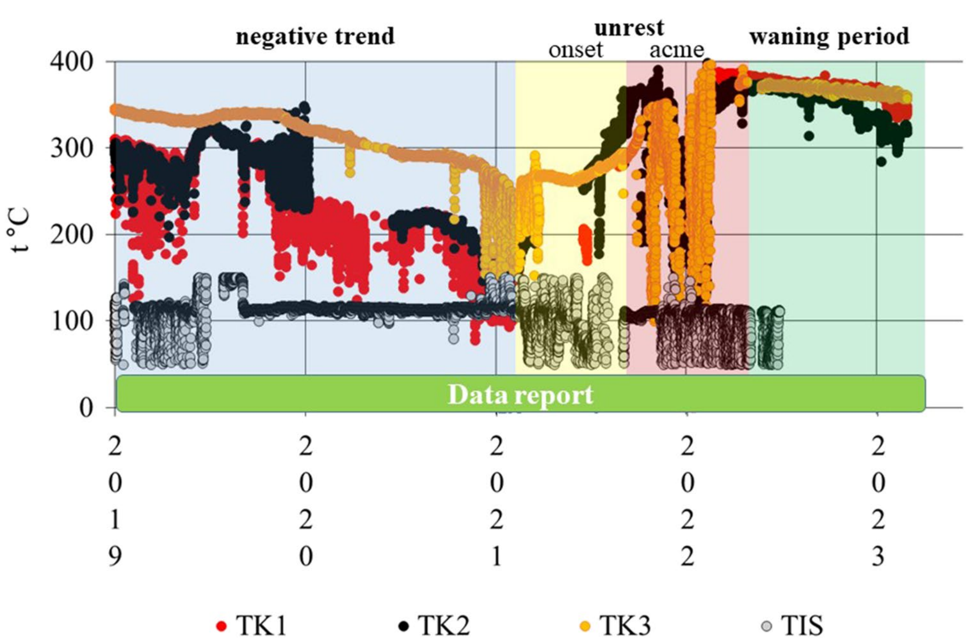

Fig. 3 Raw temperature (t, °C) data color-coded for site, recorded in the HTF on Vulcano from 2019 to March 2023. The different background colors correspond to the four evolution phases highlighted by hourly measurements: Light blue color highlight the period under decreasing thermal release; yellow and pink are for the onset and acme periods of the unrest respectively, green is for the waning period

reflect the general tendency of the thermal surface located in the summit area of La Fossa cone, having provided similar trends to those interpolated after the discrete samplings (Federico et al. 2023). Recently, the thermal monitoring time series from this close conduit volcano is also used as ground control data, to compare, integrate, and validate the new methodologies and practices of thermal remote sensing (e.g., Pailot-Bonnétat et al. 2023; Diliberto et al. 2002, 2023).

Conclusion

This Data Report presents the time series of high-temperature fumarole (HTF) data from La Fossa Caldera, covering the period from January 2019 to February 2023. These data are a part of the INGV's long-term surveillance efforts on the Island of Vulcano, begun in 1984. HTF temperatures have played a pivotal role in detecting the past and present volcanic unrest, underlining the network's sensitivity and effectiveness. Long-term monitoring displayed its ability in identifying transient processes, interpreted sometime as volcanic unrest, on the base of multi-disciplinary comparisons. Furthermore, the thermal data presented here supply critical ground control information and already contributed to the validation and improvement of emerging thermal remote sensing techniques. The integration of traditional and advanced monitoring methods has enriched our understanding of thermal variations across extensive volcanic surfaces. This Data Report provides valuable insight into the variation of convective degassing activity from La Fossa Caldera. It underlines the importance of continuous monitoring efforts and the potential of combining various monitoring methods to enhance our ability to detect and understand volcanic unrest.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00445-024-01720-0

Funding This research was funded by the INGV-DPC (Istituto Nazionale di Geofisica e Vulcanologia—Italian Civil Protection Department) volcanic surveillance program of Vulcano Island. This study has benefited from funding provided by the Italian Presidenza del Consiglio dei Ministri—Dipartimento della Protezione Civile (OvFu 0304.010). This paper does not necessarily represent DPC official opinion and policies.

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