Anatomy of a fumarole field; drone remote sensing and petrological approaches reveal the degassing and alteration structure at La Fossa cone, Vulcano Island, Italy

Daniel Müller[1], Thomas R. Walter[1], Valentin R. Troll[2,3], Jessica Stammeier[1], Andreas ~~Karlsson[3]~~ Karlsson[4], Erica de ~~Paolo[4]~~ Paolo[5], Antonino Fabio ~~Pisciotta[5]~~ Pisciotta[6], Martin Zimmer[1], Benjamin De Jarnatt[1]

[1] GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany
[2] Dept. of Earth Sciences, Natural Resources and Sustainable Development, Uppsala University, Sweden
[3] Istituto Nazionale di Geofisica e Vulcanologia (INGV), Rome, Italy
[4] Department of Geosciences, Swedish Museum of Natural History, Box 50007, SE-104 05 Stockholm, Sweden
[5] University of Milano-Bicocca, Department of Earth and Environmental Sciences, Piazza della Sciencza 4 – 20126 Milano, Italy
[6] Istituto Nazionale di Geofisica e Vulcanologia (INGV), Palermo, Italy

Correspondence to: Daniel Müller (dmueller@gfz-potsdam.de)

Abstract. Hydrothermal alteration and mineralization processes can affect the physical and chemical properties of volcanic rocks. Aggressive acidic degassing and fluid flow systems often lead to changes in the appearance of a rock, such as changes in surface coloration or intense bleaching. Hydrothermal alteration can have far-reaching consequences for rock stability and permeability, yet limited knowledge exists on the detailed structures, extent, and dynamic changes that take place near the surface of hydrothermal venting systems. By integrating drone-based photogrammetry with mineralogical and chemical analyses of rock samples and surface gas flux, we investigate the structure of the evolving volcanic degassing and alteration system at the La Fossa cone on the island of Vulcano, Italy. Our image analysis combines Principal Component Analysis (PCA) with image classification and thermal analysis, through which we identify an area of approximately 70,000 m² that outlines the maximum extent of hydrothermal alteration effects at the surface, represented by a shift in rock color from reddish to gray. Within this area, we identify distinct gradients of surface coloration and temperature that indicate a local variability of degassing and alteration intensity and define several structural units within the fumarole field. At least seven of such larger units of increased activity could be constrained. Through mineralogical and geochemical analysis of samples from the different alteration units, we define a relationship between surface appearance in drone imagery and the mineralogical and chemical composition. Alteration gradients in surface color from reddish to gray correlate with a reduction of Fe_2O_3 from up to 3.2 % in the unaltered regime to 0.3 % in the altered regime, and the latter coincides with the area of increased diffuse acid gas flux. As the pixel brightness increases towards higher alteration gradients, we note a loss of the initial (igneous) mineral fraction and a change in bulk chemical composition with a concomitant increase in sulfur content from close to 0 % in the unaltered samples to up to 60 % in samples from the altered domains. Using this approach of combined remote sensing and in situ analyses, we define and spatially constrain several alteration units and compare them to the present-day thermally active surface and degassing pattern over the main crater area. The combined results permit us to present a detailed anatomy of the La Fossa fumarole field, including high-temperature fumaroles, and seven larger units of increased alteration intensity, surface temperature, and variably intense surface degassing. Importantly, we also identify apparently sealed surface domains that prevent degassing, likely as a consequence of mineral precipitation from degassing and alteration processes. By assessing the thermal energy release of the identified spatial units quantitatively, we show that thermal radiation of high-temperature fumaroles accounts for < 50 % of the total thermal energy release only, and that the larger part is emitted by diffuse degassing units. The integrated use of methods presented here has proven to be a useful combination for a

detailed characterisation of alteration and activity patterns of volcanic degassing sites and has potential for application in alteration research and for monitoring of volcanic degassing systems.

1 Introduction

1.1 Volcanic degassing and hydrothermal alteration

Volcanic degassing at the Earth's surface is typically expressed in the form of localized fumarole fields and diffuse ~~gas escape, yet~~degassing. Yet, the association of localized and diffuse degassing is not well constrained. A fumarole is a vent or opening in the Earth's surface that releases steam and gas, including sulfur dioxide, carbon dioxide, and hydrogen sulfide, into the atmosphere (e.g. Giggenbach, 1996; Giammanco et al., 1998; Halldorsson et al., 2013). Fumaroles are typically found near volcanic areas or geothermal regions where there is intense heat beneath the surface. Fumaroles are of interest to scientists studying volcanoes and geothermal systems, as they provide information on the composition of underlying magmatic systems, the degassing processes of such magmatic systems, and the dynamic changes in the degassing passways exploited by such systems (e.g. Chiodini et al., 1993; Aiuppa et al., 2005; Paonita et al., 2013). The gas emissions by fumaroles, moreover, provide information on the possible interaction between underground water and hot rocks or magma and thus the state of a hydrothermal system through time (e.g. Chiodini et al., 1993; Capasso et al., 2000; Nuccio et al., 2001; Troll et al., 2012; Paonita et al., 2013).

The degassing of hot and acid volcanic gasses leads to versatile fluid-rock interactions at the surrounding volcanic rock, summarized as hydrothermal alteration (Pirajno, 2009; Chiodini et al., 2013; Fulignati, 2020). Alteration can affect the mineral assemblage by dissolution and remineralization up to complete destruction of the original mineral matrix and eventually influence essential rock parameters with potentially far-reaching consequences for the shallow hydrothermal system and the stability of a volcanic building (Reid & Brien, 2001; Heap & Violay, 2021). Mechanical strength tests of hydrothermally altered rocks showed considerable mechanical weakening (e.g. Frolova et al., 2014; Heap et al., ~~2019, Julia et al., 2014~~2021a, Darmawan et al., 2022), which is usually accomplished by mineral dissolution and mineral re-precipitation that affect rock strength and permeability and can in cases even seal gas pathways. Hydrothermal alteration can thus lead to sealed rock masses and hence to pressure build-up in a shallow volcanic system and consequently influence volcanic activity (e.g. Heap et al., 2019~~.~~) and increase the likelihood of flank deformation and collapse (Heap et al., 2021b). It is therefore important to better understand the degassing and alteration structures in active hydrothermal crater regions of hazardous volcanic systems.

In this study of the fumaroles of La Fossa Vulcano Island - Italy, we aim to detect and quantify alteration-related spatial and compositional parameters in order to provide improved insight into the dynamic changes of hydrothermal venting systems to help identify temporal and potentially critical developments and to better understand the associated features of diffuse and localized degassing.

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1.2 Structure and extent of degassing sites

Recent advances in volcanic geothermal areas suggest that fumaroles are often only localized expressions of a much larger area of degassing (e.g. Toutain et al., 2009; Liuzzo et al., 2015). Indeed, fumaroles and hydrothermal degassing zones are often accompanied by broader fields of activity, characterized by diffuse degassing processes, associated mineral changes, and intense surface recoloration (e.g. Donoghue et al., 2008; Berg et al., 2018; Darmawan et al., 2022) and fumaroles activity can vary in time (Troll et al., 2012; Fischer et al., 2015) and in size (Lynch et al., 2013; Gertisser et al 2023). Previous works at Vulcano, for instance, have shown that fumaroles are surrounded by extensive areas of diffuse degassing (Carapezza et al., 2011; Chiodini et al., 2005; Manini et al., 2019). Our previous work showed that diffuse degassing leads to distinct zones ~~classified~~of activity that can be identified by temperatures and visual expression (Müller et al., 2021). Those diffuse zones are ~~also~~typically constrained based on CO_2 measurements but are also subject to the diffuse flow of acid gas driving díffuse alteration processes. However, these diffuse degassing and alteration processes are often difficult to recognize without specialized sampling strategies (Toutain et al., 2009), leading to a limited understanding of the anatomy and extent of degassing and alteration systems. Understanding the dynamic changes and internal architecture of hydrothermal activity of fumarole fields and the true dimensions of their field of activity is of relevance for the study of volcanic ~~hazards~~activity and ~~resources~~hazard potential.

1.3 Surface effects and remote sensing of alteration

Hydrothermal alteration can cause significant changes in the physical and chemical properties of volcanic rock, such as density, compressive strength, and permeability (e.g. Donoghue et al., 2008, 2010; Berg et al., 2018; Heap et al., 2019; Darmawan et al., 2022). The replacement of primary minerals by secondary minerals, element mobility of fluid-mobile components, enrichment of refractory elements, and physical and textural changes of rock properties are often accompanied by changes in the color or spectral reflectance characteristics and can be traced employing remote sensing techniques.

Several studies have investigated the relationship between coloration and hydrothermal alteration. The use of rock color or spectral reflectance particularities as an indicator of alteration has been explored since the 1970s and led to the development of a variety of remote sensing techniques using satellite imagery from ETRS multispectral imagery (Rowan et. al., 1976), Landsat Thematic mapper mission (Carranza et al., 2002), ETM+ (Mia et al., 2012) or ASTER data (Di Tommaso et al., 2007) or hyperspectral analysis (e.g. Van De Meer et al., 2012; Tayebi et al., 2015). These techniques can detect subtle changes in color that may not be visible to the naked eye, allowing for the identification of mineral deposits (Mielke et al., 2016), hydrothermal alteration, or volcano stability (Kereszturi et al., 2020).

However, for analyzing details of localized degassing and alteration systems, the resolution of satellite data often is a limiting factor. Some of the best available optical satellite data have a resolution of 0.5 m in the nadir acquisition position. The

resolution of thermal satellite data is on the order of tens to hundreds of meters per pixel. That allows the general detection of degassing and alteration systems, but the imaging of details of such systems requires the use of very high-resolution data. Modern UAS (unmanned aerial systems) equipped with high-resolution sensors allow imaging of volcanic surfaces at cm scales and, therefore, permit the analysis of degassing and alteration systems in great detail. In combination with Structure from Motion (SfM) processing, they are efficient for first-site investigations and allow the creation of high-resolution structural maps to identify structures of degassing systems to assist first-order hazard analysis or guide further in-depth studies.

1.4 Aim of the study

The aim of this work is to image and analyze the degassing and alteration structure of the La Fossa fumarole field and the wider field of activity and better understand the association of diffuse and localized degassing at a fumarole field and alteration at degassing sites. We advance previous results (Müller et al., 2021) by considering new data, and by integrating them with the mineralogical and chemical analysis of alteration distribution in collected rock samples. We show systematic changes in the effects of alteration on the surface coloration and how drone-derived RGB data (Red, Green, Blue, standard color coding of images) can be used for the efficient detection and classification of degassing and alteration features. Combining UAS-based optical and infrared remote sensing with mineralogical- and geochemical analysis, and diffuse surface degassing measurements, we can infer the detailed anatomy of degassing and alteration systems at the surface, highlight active degassing domains versus areas of surface sealing, and determine their importance for the system based on their contribution to the total thermal energy release.

2 Study area

Vulcano is the southernmost of a group of 7 small volcanic islands forming the Aeolian Archipelago north of Sicily. They are located within the Aeolian Tindary Letojanni Fault System (ATLFS), an NNW-SSE striking local deformation belt connecting the central Aeolian Islands with the eastern section of Sicily (Barreca et al., 2014; Cultrera et al., 2017). The ATLFS is the interface between two larger tectonically active compartments, an extensive one in the northeast and a contractional one in the west (Cultrea et al., 2017). Frequent seismic activity and right lateral extensional displacements indicate ongoing tectonic activity (Billi et al., 2006) and the active shaping of the islands.

Vulcano is made up of volcanic edifices of which the northern section of the islands is the most recently active. The oldest volcanic activity at Vulcano is reported for 130 ka (De Astis et al., 2013). Six main stages of volcanic activity have been identified (De Astis et al.1997), of which the geologically younger active parts, the La Fossa Cone and Vulcanello, have been active during historical times <8 ka, showing mainly vulcanian and strombolian activity (De Astis et al., 2013). The last eruptive period of the La Fossa Cone from 1888-1890 was characterized by strong phreatic eruptions and witnessed and documented by Guiseppe Mercalli who later coined the term Vulcanian eruptions (Clarke et al., 2015).

Vulcano since then ~~is~~has been in a quiescent period and volcanic activity mainly ~~expresses~~expressed in degassing. Gases are provided from a magmatic-hydrothermal system fed by a shallow magmatic reservoir beneath La Fossa volcano. The hydrothermal system is likely to have been partitioned into a hypersaline brine and a vapor phase (Henley and McNabb, 1978). The denser brine phase is confined at depth and contributes to the formation of metasomatic facies observed in deep-seated xenoliths (Adrian et al., 2007). The vapor phase, enriched with SO_2, H_2S, HCl, and HF, ascends to the surface and partly emerges directly from the high-temperature fumarolic field (Bolognesi and D'Amore, 1993; Chiodini et al., 2000; Capasso et al., 1997).

Volcanic degassing is present throughout the entire central and northern part of the island concentrating in degassing clusters at Baja Di Levante, within Vulcano Porto, and in clusters along the base and summit of La Fossa Cone (Chiodini et al., 1996~~;~~; Carapezza et al., 2011~~;~~; Diliberto et al., 2021~~;~~; Inguaggiato et al., 2022 and many others) where frequently higher fluxes of CO_2 are observed. The most prominent degassing sites are the high-temperature fumaroles at the summit of Vulcano that occur in several clusters on the outer rims of La Fossa cone and are most prominent in the high-temperature fumarole field (Figure 1). Degassing at the summit of La Fossa is persistent but subject to fluctuations. Gases of the high-temperature fumaroles (HTF) emerge with temperatures > 300 °C, but temperatures have been exceeded ~~in the past.~~during previous volcanic crises (Harris et al., 2012; Diliberto, 2017). Temperatures of ~~>500~~up to 690°C were reported ~~(Harris et al., 2012, Diliberto, 2017)~~ ~~during previous volcanic crises.~~in May 1993 by Chiodini et al. (1995).

~~Several periods~~Periods of unrest ~~have been reported and~~ were accompanied by increasing fumarole temperatures (Harris et al., 2012~~;~~; Diliberto, 2013~~;~~; Madonia et al., 2013~~;~~; Diliberto, 2017), increasing soil and groundwater temperatures (Capasso et al., 2014), changing gas compositions (Paonita et al., 2013), changes in gas flux (Inguaggiat et al., 2022), or a spatial growth of the fumarole field (Bukomirovic et al., 1997). The most recent crisis occurred in 2021 and led to increased thermal radiation (Coppola et al., 2022), deformation (INGV Bulletin reports), and localized structural changes like the formation of new major fumarole complexes. The rapid dynamics during volcanic crises and potentially negative effects of alteration on permeabilities, and therewith the potential to drain gases from the surface, highlight the importance of a better understanding of the structure and state of degassing systems.

Early studies about the structural setup of the Grand Cratere fumarole field of the La Fossa Cone were provided by Bukumirovic et al. (1997) and later modified (Madonia et al., 2016~~;~~; Harris et al., 2009). Fulignati et al. (1999) analyzed alteration facies at Vulcano and constrained the central crater region to be a large silicic alteration complex characterized by the presence of chalcedony and amorphous silica. Outwardly to the central silicic alteration zone, advanced argillic (alunite ± gypsum) alteration develops, probably originating from the progressive neutralization of the acid fluids by weathering and dilution by meteoric waters (Fulignati et al., 1998). Müller et al. (2021) previously showed that degassing and alteration can be traced from remote sensing data far beyond the extent of the high-temperature fumarole locations. Based on surface color variability due to degassing and alteration processes they showed evidence for a more complex setup with alteration gradients within the silicic alteration complex and important structural units that will be complemented here. Examples ~~for~~of degassing and alteration-related surface color variability are shown in Figure 2.

3 Data and methods

To analyze the degassing and alteration structure at Vulcano, we used a combination of UAS-derived remote sensing data (optical and thermal infrared imagery), image analysis, and field-based ground-truthing by mineralogical and geochemical analysis of rock samples and surface degassing measurements. A simplified sketch of the workflow is shown in Figure 3.

1) An anomaly detection (~~chapter~~Chapter 3.2) based on UAS-derived data, employing image analysis techniques like Principal Component Analysis (PCA), and spectral and thermal classification (similar to Müller et al., 2021) provides the detailed optical and thermal anomaly pattern. Anomalies can be revealed based on slight color changes in the volcanic surface that occur due to degassing and hydrothermal alteration processes, or increased surface temperatures.

2) To verify observed anomalies, we carried out ground-truthing by mineralogical (XRD - X-Ray ~~Diffraction~~diffraction) and geochemical (XRF - X-Ray ~~Fluorescence~~fluorescence) lab analyses of representative rock samples. Further, we performed surface degassing measurements to image the present-day degassing pattern and compared it to the observed anomaly pattern. Combining this information we can infer a detailed anatomy of the degassing and alteration structure at the surface and define and parameterize major structural units.

3) A temporal ~~Infrared~~ infrared monitoring carried out from 2018 to 2022, covering the volcanic crisis 2021 at Vulcano allows us to monitor the thermal evolution and response of the identified units to an event of increased gas flow with further implications of critical processes like localized surface sealing.

Details on the single analysis steps are provided below.

3.1. Acquisition and processing of UAS-based optical and thermal infrared data

The data acquisition was performed using a DJI Phantom 4 Pro quadcopter, equipped with a gimbal-stabilized 20 MP camera with a real shutter system, recording up to 0.5 HZ. Optical overflights were performed in the daytime at an altitude of 150 m above the fumarole field, ensuring a minimum overlap of 90 % for later photogrammetric processing. Thermal infrared image data was acquired by a Flir Tau 2 radiometric thermal infrared camera system attached to the DJI Phantom 4 Pro. The FLIR Tau 2 measures in the spectral range of thermal infrared between 7.5 and 13 µm, has a resolution of 640 x 512 pixels, and is a fully radiometric sensor system. The infrared image data is recorded at 8 Hz by a Teax Thermal Capture 2 data logger. The camera was attached to the copter with a standard camera bracket on a self-made carrier frame and is powered by an external 11.1 V lithium-polymer battery, supplying voltage to the camera system (transformed down to 5.2 V in) and to an external GPS antenna (>~~8V~~ 8 V required) which provides coordinates for each infrared image. Infrared overflights were performed in the early morning hours, before the sun illuminates the crater area, to avoid disturbances of irregular surface heating due to solar radiation exposure (Stevenson and Varley, 2008). In this way, we ensure to map the thermal signal from the hydrothermal system exclusively.

478   All image data were processed using the Structure from Motion (SfM) approach in Agisoft Photoscan (Version 1.5.2.7838).

479 The image data were inspected and images were preselected ensuring an overlap of 90 %. Images of poor quality or out of

480 focus were excluded and only images of a constant flight altitude were used for the processing. This is particularly important

481 for the processing of infrared data, as varying altitudes might alter the radiation information due to changing pixel size to vent

482 ratios. The infrared data was pre-inspected in Thermoviewer 3.0 and exported in a 16-bit tiff format in grayscale. We followed

483 the typical workflow of sparse point cloud-, dense point cloud- and mesh generation, aiming to obtain a 3-dimensional model

484 and eventually orthomosaic, digital elevation model (DEM), and infrared mosaic. The original images and processing results

485 are roughly georeferenced, but their geolocation was optimized by manual co-registration using the ArcGIS georeferencing

486 toolbox. An overview of the acquired and processed data sets can be found in Table 1.

487

488 **3.2 Anomaly detection - Principal Component Analysis (PCA) and spectral classification for alteration mapping**

489 The alteration mapping was performed on an orthomosaic data set acquired in 2019 that, due ~~a~~to poor fumarole activity,

490 provides an almost distortion-free image of the central crater region. ~~Using an approach similar to Müller et al., (2021), the~~The

491 alteration structure was revealed-, similar to Müller et al. (2021), by applying a Principal Component Analysis and image

492 classification allowing further constraints on the zonation of the fumarole area and expanding the interpretation by geochemical

493 and mineralogical analyses of rock samples for ground truthing. PCA is a statistical tool that was invented by Pearson (1901),

494 further developed and widely applied in remote sensing or image analysis (e.g. Loughlin, 1991; Fauvel et al., 2009; Alexandris

495 et al., 2017). It can detect and highlight optical anomalies within an RGB data set by transforming the data values of the initial

496 RGB channels onto their perpendicular axes of the highest data variance. ~~The resulting Principal Components are variance~~

497 ~~representations~~ (e.g. Abdi & Williams, 2010). This can be achieved in several ways. We used the PCA implemented in the

498 ArcGIS image analysis toolbox (see ArcGIS online documentation for Principal Component Analysis), performing the

499 following workflow. In the first step, an ellipse including all data points is calculated for each dimension (RGB). The main

500 axes of these ellipses represent the Eigenvectors (direction of highest variance), and will be used as a new coordinate system

501 for the data transformation. By transforming all data points onto this new coordinate system, we obtain Principal Components

502 (PC) which are variance representations of the initial RGB image data and can be used to detect and highlight optical anomalies

503 like color changes due to alteration processes- (Müller et al., 2021, Darmawan et al., 2022). PCA further promotes a

504 decorrelation of the initial RGB bands, a dimensionality reduction, and associated better data separability so that color

505 variations, before expressed by changes in the three RGB bands (3-dimensional problem), can now be accessed in single bands,

506 the single Principal Components (PC). While Principal Component 1 (PC) resembles ~91.3 % (95) of the initial data variance,

507 it mainly shows brightness changes within the image. PC 2 and 3 contain 7.4 (4.5) and 2.3 (0.5) % of the data variance,

508 resemble color changes, and are suitable to resolve optical anomalies related to hydrothermal alteration.

540 ~~Hydrothermally~~In our data, hydrothermally altered areas were defined based on the PC3, with pixel values > 85 representing

541 hydrothermal alteration. We used this as a mask to crop the respective pixel locations ~~in~~from the original orthomosaic~~,~~ (RGB),

542 resulting in a 16 Mio pixel alteration raster subset~~.~~ (RGB). This alteration raster subset allows for a more sensitive image

543 analysis due to the reduced spectral range with respect to the original orthomosaic. ~~An~~Another iteration of PCA, now applied

544 to the extracted alteration raster subset adjusts to the new reduced spectral range, as we are excluding all redundant data e.g.

545 unaltered surface, and provide a variance representation of the altered surface exclusively. We classified the result in an

546 unsupervised classification (implemented in ArcGIS, using a combination of Iso Cluster and Maximum Likelihood

547 classification) with 32 classes ~~was applied to the PCA of the hydrothermal alteration raster subset and used to classify optical~~

548 ~~units.~~. We decided on unsupervised classification as this is a more data-explorative way of exploring the pixel information,

549 rather than classifying based on a spectral range constrained by training areas defined on pre-assumptions in a supervised

550 classification. The 32 classes are chosen to obtain a high class resolution, as this is the highest number of classes possible in

551 the unsupervised classification tool. By combining these classes in a way that they resemble larger optical spatial units~~best~~,

552 we eventually defined 4̶3 Types of alteration surface (Types 1-~~4) and~~3) and the unaltered surface (Type 4) and further analyzed

553 their spectral characteristics and spatial distribution. Boxplots of the distribution of RGB values in the 32 classes and the

554 spectral range of Type 1-4 surfaces are shown in Appendix A. The optical structure of the fumarole field and alteration zone

555 is similar to the thermal structure and will be discussed in Chapter 4.3̶2.

556

3.3 Infrared analysis - thermal structure and time series analysis

558 The SfM-derived infrared mosaic represents the thermal radiation in a 16-bit tiff format, resembling values between 0 and

559 65536. To obtain a temperature map from the IR mosaic we calculated the apparent pixel temperatures Tp by

$$Tp \text{ (in K)} = grayvalue * 0.04 \quad (1)$$

562 where Tp is the apparent pixel Temperature in K, the gray value is the radiation value of the original infrared mosaic and 0.04

563 is the scaling factor (radiometric resolution). The temperature map was used to define the thermal structure ~~was analyzed by~~

564 ~~defining temperature thresholds above~~. We observed several distinct thermal spatial units with temperatures significantly

565 above the background temperature, that ~~highlight thermal spatial units best. A temperature threshold of T>40°C was used to~~

566 ~~highlight~~ can be distinguished in high-temperature ~~fumarole~~fumaroles (HTF in the following) ~~locations and a threshold of~~

567 ~~>22°C 40°C (min. 5 °C above background) highlights~~ and areas of ~~a~~rather diffuse thermal surface heating (Figure 4 B/D). To

568 constrain these units spatially for further comparison, we had to approximate spatial boundaries what was done after

569 comparison to our optical data and based on knowledge of previous observations by defining the temperature thresholds of T

570 = 22-40°C for the diffuse heated areas and T > 40°C for HTF. The 40°C threshold resembles well the known locations and

9

extent of HTF in the upper and lower fumarole field. To compare the thermal emissions of detected structural units, we calculate radiant flux and the radiant exitance values by applying the modified Boltzmann law.

$$Q=e*b*A*(Tp^4-To^4) \quad —(2)$$

The emissivity (e) was assumed to be 0.95 (often used as an assumption for volcanic surfaces), the Boltzmann constant (b) is 5.670737×10^{-8} Wm-2K4, the area of a pixel (A) is 0.024 m². *Tp* is the pixel temperature and *To* is the average background mean temperature, calculated based on 9 reference areas that are anomaly free. free. To compare identified units quantitatively, we summarized the radiation per pixel for the respective units a-g to a cumulative thermal radiation (Rcum). The flight altitude of 150 m (above the fumarole field) in combination with the low resolution of infrared sensors results in a pixel resolution of 0.38x038 x 0.38 m.

Note that remotely sensed Infrared data always represents apparent temperatures that might differ from the real object temperature due to the radiation properties of the measured object itself (emissivity), the distance of the sensor to the measured object, the pixel-to-object size ratio, but also due to atmospheric or hydro-meteorological effects (Ball and Pinkerton, 2006) influencing the detected radiation values. Therefore apparent temperatures typically are lower than in situ vent temperatures. Real fumarole vent temperatures can reach more than 300 °C (Diliberto, 2013) while temperatures in our infrared mosaic range to max. 163 °C only. With this data set, we do not aim to provide precise fumarole temperatures but to analyze the thermal structure of the fumarole field and the broader field of activity.

3.4 Ground-truthing by Mineralogical and geochemical analysis Geochemical Analysis

3.4.1 Rock sampling

Rock samples were collected at predefined representative locations aiming to include all alteration end members, during field campaigns in 2019 and 2022. We sampled along 3 transects following the postulated hydrothermal alteration gradients and crosscutting major alteration units, of which transect A is located on the lower fumarole field, transect b along the upper crater rim, and transect c is located in the eastern crater crosscutting several alteration units (locations for samples in chapter 4.2.2 Figure 7). Samples were in the size of ~2000cm³ (hand-sized) retaining the undisturbed surface crust, but also subsurface material to a depth of ~ 10 cm. The samples were mechanically crushed, ground to 63 µm, and split for XRD and XRF analysis, respectively. In total 21 samples were collected of which 9 were prepared for the XRD and XRF analysis and 12 for XRF analysis exclusively.

3.4.2 X-ray diffraction (XRD)

Between 1 and 3 mg of whole rock powder was used to determine the mineral composition of each sample through powder X-ray diffraction (pXRD). The analysis was conducted using a PANalytical X'pert diffractometer equipped with an X'Celerator silicon-strip detector at the Department of Geoscience, Swedish Museum of Natural History, Stockholm. The instrument was operated at 45 kV and 40 mA using Cu-Kα radiation ($\lambda = 1.5406$ Å). Samples were analyzed between 5° and 70° (2θ) for 20 min in step sizes of 0.017° in continuous scanning mode while rotating the sample. Data were collected with "divergent slit mode" and converted to "fixed slit mode" for Rietveld refinement. The collected data show several peaks of X-ray diffraction intensity which represent the characteristic of crystalline minerals, the proportions of mineral phases were then refined using the Rietveld refinement method in the High Score Plus 4.6e software. The XRD analytical procedure was performed twice for each sample to ensure optimal quality control. Some samples contained contents of amorphous material of more than 50 %. Those will be marked with a * in the following but we will consider the mineral composition normalized to 100 % non-amorphous material.

3.4.3 X-ray fluorescence (XRF)

Bulk chemical composition was determined by X-ray fluorescence analysis (XRF) at the ElMiE Lab at the German Center for Geosciences (GFZ). Main and trace elements were measured on fused beads with an AXIOS spectrometer (Malvern Panalytical, UK). Loss of ignition (LOI) was determined by analysis of H_2O/CO_2 using an Eltra element analyzer. Reproducibility was determined on three certified reference materials (CRM) and is within the analytical precision, which is better than 2 % for main elements and better than 10 % for trace elements.

3.4.4 Surface degassing measurements (CO_2, SO_2, H_2S)

The surface degassing was measured at ~ 200 points within the northern part of the La Fossa cone (Figure 6) in September 2021 and November 2022 using a simplified multi-gas accumulation chamber approach (Appendix B). The measurement unit, a Dräger XAM 8000 handheld Multigas device, was equipped with 6 sensors measuring CO_2, CH_4, SO_2, H_2S, H_2, and O_2 simultaneously of which CO_2, SO_2, and H_2S are considered here. The simplified accumulation chamber approach was an adaption as a consequence of uncertainties encountered in previous multi-gas measurement campaigns. Due to different sensor reaction times for ascending and especially descending gas concentrations, the comparison of direct sensor readings might lead to odd gas ratios with an artificial shift towards magmatic components. For that reason, we use the slope of the ascending gas concentration within a defined volume as quantification for a relative surface flow. More detailed information about the gas measurement approach is provided in the supplementary materials. Note that the aim of the gas measurements was not to provide accurate flux estimates but to highlight the spatial variability of the gas flow of certain gas species from the surface.

4 Results

4.1 Thermal- and optical anomaly patterns reveal the degassing and hydrothermal alteration structures

Degassing and hydrothermal alteration at La Fossa as seen in drone imagery can be traced by mainly two effects.

1) The transition from unaltered to hydrothermally altered surface can be traced by a general color shift in the drone images from reddish to grayish (Figures 2A and 4A). This allowed us to constrain a distinct ~70,000 m² sized area surrounding the fumarole field in a circumferential manner. This area is hereafter referred to as the Alteration Zone (ALTZ in Figure 4A/B), and represents the maximum extent of at-surface observable alteration effects that can be associated with the fumarole field. It includes effects ranging from weak surface alteration to strong alteration with intense surface bleaching and remineralization, to complete destruction of the host material. The extent of the ALTZ exceeds the area covered by the high-temperature fumarole (HTF) site by ~50 times (Figure 4A/B), indicating the widespread influence of diffuse degassing and alteration processes.

2) Within the ALTZ we observe a segmentation characterized by brightness and color variability expressed in different shades of gray (Figure 4A), the second optical effect, indicating local alteration gradients. Analyzing the ALTZ for this spectral variability by PCA and image classification we can constrain pixels of low-, increased-, or intense surface bleaching and alteration (light blue, dark blue, and red pixels in Figure 4B) and define an alteration index represented by 4 surface Types (1-4), of which Type 1 is the most altered and Type 4 the least altered surface.

Type 1 surfaces are bright grayish intensely bleached surfaces or sulfuric deposits and represent the strongest alteration end members that we can detect optically from our data. Type 1 mainly resembles the fumarole sites and surrounding areas (Figure 4 A/B) but also larger isolated regions that can not be associated with major vent systems. With increasing distance to the degassing centers, we observe a shift towards darker grey (Type 2) and brownish (Type 3) surface colors. **Type 2** is characterized by a gray but comparatively less bright coloring. It typically occurs at the boundaries between Type 1 and Type 3 regions and largely surrounds Type 1 areas, but it also forms several isolated clusters typically embedded in Type 3 areas (units b,d,g in Figure 4). Type 3 is generally darker and more reddish in color, similar to the unaltered parts of the crater surface, but can be well distinguished from the unaltered surfaces by PCA. It makes up ~50 % of the ALTZ and dominates in the central northern and the southeastern parts. Type 4 is a reddish, apparently oxidized surface that dominates the La Fossa cone surrounding the ALTZ.

The surfaces within the ALTZ are generally mixed and composed of more than one type. The ALTZ is characterized by a generally high density of Type 3 pixels, with locally high densities of Type 1 and Type 2 pixels, which then become the dominant surface Type and form larger spatial units, indicating locally higher alteration gradients or larger structural units (units a-g in Figure 4 and details in Appendix C). The largest of these units cover several thousand square meters each.

The thermally active surface (Figure 4C) can be divided into high-temperature fumaroles (HTF in Figure 4D) and diffuse thermally active surface (green pixels in Figure 4D). HTFs are the visible part of the activity that can be constrained by the

naked eye in the field, while the diffuse thermally active surface is largely imperceptible. The thermally active surface largely mirrors the alteration pattern observed in the optical data. An analysis of the temperatures obtained at all pixels of Type 1 to 4 surface ~~show~~shows a general increase of mean pixel temperatures from Type 4 to Type 1 surface by an average of 2 degrees (Figure 5). In particular, areas dominated by Type 1 and 2 surfaces reflect the thermal structure well while areas of Type 3 dominance largely coincide with low-temperature surfaces (Figure 4 B/D). An additional Spearman correlation test, applied to the classified surface (32 classes unsupervised, for comparison see Appendix A) and the thermal data (in °C) shows a moderate positive correlation between optical and thermal anomalies (Appendix D). This shows that the detected optical anomalies are meaningful and that degassing and alteration variability occurs even at local scales and can be traced in our close-range drone remote sensing data.

The spatial coincidence of both optical and thermal anomalies highlights the relationship between variations in the surface coloration, caused by alteration processes, and the ongoing influence of diffuse gas flow. A general coincidence of increasing brightness (simultaneously increasing the RGB values) with increasing surface temperature of an area can be constrained (Figure 5).

4.2 Anomaly structure ~~revealed~~identified from optical and thermal data

The optical and thermal anomalies form distinct spatial units of alteration and elevated surface temperature (units a-g in Figure 4D), which now allow us to infer the following surface structure of the fumarole field and its wider field of activity.

The centers of degassing activity are high-temperature fumaroles (HTF). These are the "visible" ~~part~~parts of the activity that can be perceived in the field (red pixels in Figure 4D). We spatially constrain the HTFs based on apparent temperature values with $T > \geq 40$ °C in our 150 m overflight data. Using this as a threshold we find that the HTFs cover an area of 1223 m², and occur exclusively in the Type 1 surface. However, HTFs represent only a fraction of the active surface.

The total extent of the surface that has to be considered active is much larger. The surface with elevated temperature covers ~30000 m² (green pixels in Figure 4D, $T > \geq 22$ °C or 5 °C above the background), exceeding the area covered by HTF by a factor of 25. The surface that is considered hydrothermally altered (ALTZ ~70,000 m²) exceeds the area covered by HTF by a factor of ~60, highlighting the widespread influence of diffuse degassing and alteration processes.

Besides the HTF we have constrained larger units of elevated surface bleaching and surface temperatures that can be considered structurally important and centers of diffuse degassing activity.

Units a and b are diffuse features of increased surface bleaching (Type 1 and 2) and surface temperature, embedded in the Type 3 surface and surrounding the eastern fumarole field in the form of an aureole shape. Neither can be associated with major vents. The observed maximum surface temperature for unit a is 43.7°C (0.43 m resolution) and the average temperature is 25°C, ~8 °C above the background. It is located at a distance of 25 to 50 m downslope from the eastern rim fumarole complexes, separated by a low-temperature zone (LTZ). Unit b, the southern part of the aureole is a 120 m long and 20 - 35 m wide anomaly located subparallel on the inner side of the crater. It extends over ~2100 m² and has a maximum surface temperature of 46°C and an average temperature of 26°C (9 °C above the background). The temperature range and spatial extent of units a and b are comparable. In the field, both are difficult to identify as there is little or no evidence of degassing

13

849 (Appendix E). Like unit a, unit b is also separated from the main fumarole vents by the LTZ. Its northern boundary corresponds

850 exactly to the positions and curvature of the fumarole alignments at a relatively constant distance of 30 meters. In unit b, we

851 observe a temperature gradient with higher temperatures at greater distances from the fumarole vents and an apparently more

852 active center in the ~~south-eastern~~southeastern corner. Another thermal anomaly with a similar shape and orientation is located

853 further south inside the crater.

854 Units d and f are similar aureole-like features in the western fumarole field, associated with fumarole complex F0. They

855 circumferentially surround fumarole complex F0 at a distance of 5 to 15 m, also separated from the HTF by a Low-Temperature

856 Zone (LTZ), but to a lesser extent than that observed for units a and b of the eastern fumarole field. The southwestern section

857 of this aureole, unit d, appears as a larger heated complex with stronger surface bleaching (Type 1) and higher temperature

858 (mean T=27°C), and a temperature gradient with higher temperatures further away from the major fumarole complex. The

859 boundary to the low-temperature zone is sharp with a sudden drop in temperature of 10 to 20-°C and a strong associated color

860 shift (Appendix C). The aureoles of F0 and F11 have in common that they are encircled by a network of polygonal net-shaped

861 thermal anomalies in the far field.

862 Low-temperature zones (LTZs) dominate the central parts of the fumarole field. The LTZ have only slightly elevated

863 temperatures relative to the background (18-21°C or 1-4°C above background) and can be optically constrained by a darker

864 Type 3 surface coloration. From field observations, we have ~~constrained~~concluded that these LTZ form a strong, apparently

865 sealed surface complex. Therefore LTZ might indicate largely sealed sections of the fumarole field which inhibit gas flow at

866 the surface. The 3 central LTZ1-3 (Figure 4D) cover an area of ~12,000 m².

867 Unit c is a broad complex of highly altered material (Type 1) and significantly high surface temperatures. It is potentially the

868 most altered member in the central crater region. It covers an area of ~8000 m² and the maximum and average apparent

869 temperatures observed are 87-°C and 29-°C. It is associated with the HTF FA and F58. Considering the thermal structure of

870 unit ~~e~~c, it is a heterogeneous unit formed by a network of higher temperature anomalies embedded in lower but, with respect

871 to the background, significantly increased tempered surface. This area is associated with the northwestern crater unit, which is

872 the most recent explosion crater.

873 Unit d is an area of diffuse activity associated with the inner crater part of fumarole complex F0, showing a significant shift in

874 surface colorization and temperature, some 20 m away from the fumarole complex. The boundary is distinct and visible to the

875 naked eye (Type 3 to Type 1). The temperature shift is on the order > 20 °C.

876 Unit e is a large branching thermal and optical anomaly of the upper fumarole field. It can be constrained by its gray coloration

877 embedded in the reddish unaltered surface and also by its increased surface temperature. It is a 120 to 150-m-long branch-

878 shaped network of anomalies on the inner crater wall. The central feature is oriented E-W and located ~ 20 m south and below

879 the helicopter platform and the crater rim. We constrained its size to ~2500 m² (only the western branch, without intersection

880 to ~~h~~unit d) and the recorded maximum and average apparent temperatures are 45.0-°C and 25.9-°C respectively. Some smaller

881 clusters of localized degassing, alteration, and increased surface temperature, visible at the surface by its bright coloration, are

882 observed in the northern section of the fumarole field (unit g) towards La Forgia.

916
917 **4.~~2~~3 Ground truthing - verification of observed anomalies**

918 We have carried out mineralogical (X-ray diffraction) and geochemical (X-ray fluorescence) analyses of bulk rock samples
919 collected at representative locations and surface degassing measurements. The aim is to verify the observed anomaly pattern
920 of alteration gradients and distinct active units~~,~~ and to investigate the relationship between the optical and thermal anomaly
921 pattern and modern degassing and hydrothermal alteration processes. In this way, we provide ground truthing and demonstrate
922 that the anomalies observed are significant.

923

924 **4.~~2~~3.1 Present-day surface degassing pattern**

925 The measurements of diffuse degassing from the surface allow us to compare the present-day surface degassing pattern to the
926 observed optical and thermal anomalies (Figure 6 A/B). We performed surface degassing measurements of CO_2, H_2S, and SO_2
927 simultaneously in the diffuse degassing regime at 200 measurement points (~100 points within and outside the ALTZ)
928 throughout the whole northern crater section (details of gas measurements in Appendix B).
929 The observed relative flux values for CO_2 range from 0 to ~9000 ppmv/s with an average of ~900 ppmv/s. They are
930 considerably higher ($x*10^3$) than the SO_2 and H_2S flux at the respective locations. For both, SO_2 and H_2S a maximum gas flux
931 of < 10 ppmv/s was measured and the average is below 0.5 ppmv/s.
932 Looking at the spatial distribution of the measured ~~gas~~gasses we observed generally higher gas levels within the alteration
933 zone ALTZ and at the ALTZ boundary, for each of the measured gas (Figure 6 C/D). The average CO_2 flux is 660 ppmv/s
934 outside the ALTZ and 923 ppmv/s within the ALTZ. Thus, the averaged CO_2 flux inside the ALTZ is about 1.4 times higher
935 than outside~~,~~ but is particularly high in some of the constrained units a-g. However, the CO_2 flux has a wide spatial distribution
936 and high flux values of above 2000 ppmv/s can also be observed outside the ALTZ and at a distance to the ALTZ boundary
937 (Figure 6 A/C).
938 SO_2 and H_2S in contrast appear spatially ~~stronger~~more strongly confined, and significant flux values can be exclusively
939 observed within the ALTZ (Figure 6 B/D). Values for SO_2 and H_2S inside the ALTZ exceed the outside-ALTZ values by 13
940 and 15 times. This higher diffuse flux, although at average low concentrations, might promote a surficial process of chemical
941 weathering and surface bleaching, potentially causing the observed color shift from a reddish-oxidized surface toward gray
942 and will be discussed further based on analyses of the geochemical composition of rock samples in Chapter 5.2.
943 Comparing the surface degassing to the observed optical and thermal anomaly pattern (Figure 6 E-G), we see that high values
944 were observed especially in units a or b on the eastern side of the fumarole field, coincident with increased alteration (Type 1
945 and 2) and thermally active surface, followed by other constrained units c-g. However, the strongly bleached and apparently
946 highly altered unit c shows, other than expected, rather small ~~values~~gas fluxes, although its surface temperature is significantly
947 increased with respect to other identified units. This might indicate reduced surface permeability and surface sealing processes
948 and will be discussed in ~~chapter~~Chapter 5.3.

15

981 While SO$_2$ or H$_2$S flux values for Type 1 and 2 surfaces are increased, only low fluxes were constrained for the Type 3 surface

982 and no flux for the unaltered surface (un in Figure 6 E-G). Note that the central sections of the fumarole field were not sampled

983 due to the close vicinity to HTF and expected high flux values. The data shown here is only representative for the diffuse

984 degassing domain.

985

986 **4.23.2 Mineralogical composition of the alteration gradients**

987 XRD Analysis was performed along two transects A and B, and XRF analysis was performed on samples taken along three

988 transects A-C (Figure 7), crossing postulated alteration gradients.

989 Transect A crosses from the unaltered surface over Type 3 into the Type 1 surface (T3-T1 boundary in Figure 7) of the highly

990 altered unit c. Transect B is oriented along the HTF on the crater rim in an east-west orientation from Type 1 surface into the

991 LTZ (Type 3). Transect C crosses the eastern fumarole field from the unaltered surface, through the Type 1 and 2

992 surfacesurfaces in unit B, the LTZ (Type 3) on both sides of the HTF, to Type 1 and 2 surfacesurfaces, and eventually the

993 unaltered material outside the ALTZ. This transect represents the variability in the rather diffuse degassing regime as no

994 samples close to the HTF were used for the analysis.

995 Results of all samples support local alteration gradients within the ALTZ and show significant changes in the mineralogical

996 and geochemical compositions (Table of XRD results in Appendix F). The dominant mineral phases observed in samples of

997 transects A and B are sanidine, cristobalite, and elemental sulfur (Figure 7). Additionally, most samples contain amorphous

998 material, representing glassy phases typical for volcanic sequences. For comparability, mineralogical concentrations refer to

999 the crystalline phase, while amorphous contents are stated with respect to the total. Note, however, that bulk rock geochemistry

1000 refers to both phases and cannot analytically distinguish between amorphous and crystalline.

1001 Considering compositional changes along transect A we observe a high proportion of sanidine feldspar and lesser cristobalite

1002 in the relatively unaltered samples (Type 4). With an increasing degree of alteration, we observe a general loss of cristobalite

1003 and sanidine while sulfur contents increase (Figure 7). Samples from the unaltered reddish Type 4 surface (A1) outside the

1004 ALTZ and Type 3 surface (A2/3) inside the ALTZ are similar in composition and show high sanidine and cristobalite contents

1005 of 86-87 % and 13-14 % in the crystalline part, respectively, yet low to no sulfur contents. These samples were taken in areas

1006 of no or only slightly increased surface temperatures of < 22 °C (i.e. < 5 °C above the background). Samples A4-6 are taken

1007 in unit c, a complex of high alteration and increased mean surface temperatures of 28°C (~10°C above background). In this

1008 strongly altered unit, cristobalite is absent, along with a decrease in sanidine to 60-70 % relative to the least altered samples

1009 and an increase in sulfur contents of up to 20-40 % in the crystalline portion of the rock sample. However, the amorphous

1010 components constitute a high proportion of these sample(s), showing ca. 50 % in samples A6 and B1.

1011 Samples taken on the upper rim along transect B in the high-temperature fumarole regime (V-AHT) contain total sulfur

1012 contents of 50 to 100 %, while cristobalite is absent in these samples. Sample B3, a piece of grayish crust is taken from LTZ3

16

(~21°C, 4°C above background) in between the high-temperature fumaroles F0 and F5 and contains 100 % sulfur, highlighting the precipitation and sealing potential of degassing activity at the surface.

Comparing the changes of surface coloration with changes in the mineralogical composition we can constrain no significant effect at the ALTZ boundary, i.e., the transition from unaltered to altered surface (A1-A2/3), although the optical effect is major. However, significant compositional changes, e.g. the complete loss of cristobalite and increasing sulfur content are observed at the ALT - AMT boundary (blue mark in Fig. 6), coincident with the shift from Type 3 to Type 1 surface into unit c.

4.2~~3~~.3 Bulk geochemical composition of the alteration gradients

For samples without amorphous fraction, bulk geochemical composition correlates reasonably well with mineralogy determined by XRD, assuming ideal stoichiometry. The difference between theoretical bulk composition and true composition is within 10 % of the respective element, which we consider a good estimate given sample heterogeneity. Only for sample A5, the high Mn content remains unmatched by XRD analysis. Subtracting the theoretical bulk composition of the crystalline fraction from the true bulk composition, we can thus estimate the chemical composition of the amorphous fraction. The amorphous fraction is similar to the crystalline counterpart mainly composed of SiO_2 and some minor (< 5 wt%) phases, as well as elevated Mn contents. The high Mn contents were only observed in samples with medium alteration and elevated temperatures, both in samples with and without a significant contribution portion of amorphous material. It is thus likely that Mn is contained in the crystalline phase, yet could not be detected due to the high SiO_2 signals derived from sanidine and amorphous material.

The bulk geochemical composition (Figure 7 and data table in Appendix G) agrees with the mineralogical composition. All samples are high in SiO_2 content and, therefore, can be considered to belong to the large ~~silie~~silicic-alteration complex earlier described by Fulignati et al. (1999). The samples show a slight variability of SiO_2 between 67-82 wt. % and plot on the rhyolite field within the TAS diagram (Middlemost, 1994; not shown here). The amorphous component, typical for rhyolite, consists of mainly SiO_2, with minor amounts of Fe and Al, based on the difference between the theoretical and actual geochemical composition calculated from stoichiometric mineralogy. Three samples also have significant MnO, possibly caused by hydrothermal leaching and precipitation as amorphous crusts. However, the variability of MnO will not be detailed further in this study.

Dominant in transect A is the loss of Al_2O_3 from the unaltered Type 4 surface (> 10 wt.%) outside ALTZ to the Type 1 surface of the highly altered unit c (< 0.4 wt.%). Similarly, Fe_2O_3 is decreasing from an average of 1.6 to 0.3 wt.%. The loss of Al_2O_3~~,~~ and Fe_2O_3 is likely related to the alteration of sanidine and the elution of iron- and aluminum-sulfates formed due to the contact with sulfuric gas. The most significant changes occur, similar as observed in the mineralogy, not at the transition from unaltered to altered (ALTZ-boundary) but at the ~~ALT-AMT~~T3-T1 boundary (blue line in ~~figure~~Figure 7) at the transition from Type 3 to Type 1 surface.

17

Transect C crosses from the unaltered surface through unit a, the northern LTZ, the southern LTZ, unit b, Type 3 surface, and eventually the unaltered surface. Compositional changes from unaltered (Type 4) to altered (Type 1 and 2) surface of units a and b, here, are minor with relatively stable values for Al_2O_3 (6-12 %), Fe_2O_3 (1-3 %), TiO_2 (< 0.5) and Mn (~0). At the transition from active units a and b (Type 1 and 2 surface) to the LTZ (Type 3), we observe a significant increase of sulfur content from < 2 % to 12-40 %. However, this increasing sulfur content here is not coincident with the systematically brighter surface color observed for other altered units. LTZ show the same rather dark surface observed for Type 3 surface elsewhere, which is a discrepancy to the effects observed in the western fumarole field and indicates that LTZ have to be considered subject to different surficial processes. This will be discussed in ~~chapter~~Chapter 5.3.

5 Discussion

~~In this study, combining close-range remote sensing, image analysis, mineralogical and geochemical analyses of rock samples, and the investigation of the present-day surface degassing, we investigate the degassing and alteration structures of the fumarole field and the broader field of activity at La Fossa cone on Vulcano. Based on image analysis (similar to Müller et al., 2021) of new better quality drone-derived high-resolution image data, we resolve the general pattern of degassing and alteration effects at the surface, spatially constrain them and complement our previous work with more detail and extensive ground truthing. In our previous work parts of the central fumarole field could not be analyzed in detail due to stronger gas plume distortion in our image data. Also, some parts of the results presented here are results of additional and intense fieldwork and lead to an adapted interpretation of observed effects especially considering the diffuse activity pattern in the eastern fumarole field.~~

~~From UAS-derived RGB imagery, we identified a ~70,000 m² sized zone that is outlining the maximum extent of observable alteration effects. We showed variability within the ALTZ that represents local alteration gradients or structural units. We show that effects of diffuse degassing and alteration can be traced far beyond the activity of high-temperature fumaroles. Alteration effects can be observed in an area (ALTZ) that is actually ~50 times larger, and a thermally active surface that is ~25 times larger than the area covered by high-temperature fumarole complexes.~~

~~Analyses of mineralogical and bulk~~ Various studies have previously explored the geochemistry (e.g. Fulignati et al., 1999), petrology (e.g. De Astis et al., 1997), geophysics (e.g. Revil et al., 2008) and remote sensing signal (e.g. Mannini et al., 2019; Coppola et al., 2022) of the La Fossa crater, Vulcano island. In this study, we combine close-range remote sensing, image analysis, mineralogical and geochemical analyses of rock samples, and the study of the present-day surface degassing of the La Fossa crater and analyse the surface expression of hydrothermal activity. Through this combination of ultra high resolution (< 10 cm) drone image analysis with mineralogical/geochemical analysis, we are able to provide a holistic picture of the surface

degassing and hydrothermal alteration pattern, highlighting an aureole-like organisation of the alteration field that distinguishes distinct units that grade from inner high-temperature fumaroles to sealed surfaces (LTZ) and to diffuse degassing areas at a greater distance. An area of approximately 70,000 m², which we have termed the Alteration Zone (ALTZ), outlines the maximum extent of observable alteration effects and highlights that degassing and alteration can be traced well beyond the central high-temperature fumarole activity sites (HTF). The ALTZ is similar to the diffuse flux zone previously identified by Mannini et al. (2019), and is in fact ~50 times larger than the area covered by the high-temperature fumarole domain. However, from the optical data, we observe further variability within this zone expressed in active units a-g, which also coincide with the diffuse thermal activity and cover 25 times the extent of HTF. Here we can further detail the surface structures and activity patterns identified in previous works, (e.g. Harris et al., 2009; Mannini et al., 2019) which divide the active region into a vent flux zone and a diffuse flux zone. In particular, we can further detail the vent flux zone by outlining high-temperature fumarole locations based on high-temperature pixels. We further show that thermal radiation and gas flux of the ALTZ or diffuse flux zone are not uniform but show strong local variability, with high fluxes in identified active units a-g and low fluxes in larger parts of the central fumarole field associated with LTZ (Low-Temperature Zones) or the unaltered regime.

Although the structural study is based solely on drone-derived imagery and thermal infrared data, our detailed observations of local activity and alteration gradients are supported by variations in mineralogical and bulk geochemical compositions of representative rock samples support our observations of local strong alteration gradients and allow to constrain relations between remotely sensed surface coloration and degassing and alteration processes. A. Although we have performed a classification of the image data in this work, already visual observations can show a general shift from reddish to gray surface coloration allows us to infercolor, which coincides with areas of increased diffuse gas flow. VariabilitySuch color anomalies can therefore be used as guide in the field. A variability in surface brightness and gray hues allows for the detection ofcoincides with alteration gradients and major active units. A largely coincident, and the congruent optical and thermal anomaly pattern highlightsindicate the relationlink between surface temperature and surface color and allows to constrain major structural units. Some of these units represent large complexes of diffuse activity and are apparently important structural features for the degassing system as will be discussed in chapter 5.3.

The coloration and degassing-induced alteration processes. This relationship underlines the potential of the presented combination of methods providesas an efficient tool for first-order site investigation oftool for volcanic degassing and alteration systems andthat can be applied to volcanoes elsewhere. Structural findings and implications for the degassing and alteration system provide information for further and more detailed alteration research.

5.1 Alteration Zone (ALTZ) controlled by sulfuric gassesgases and elution processes

The ALTZ, is characterized by a surface color shift from reddish to gray, is coincident and coincides with the area of higher SO₂/H₂S flux and apparently represents theappears to represent a zone of diffuse acid gas flow (Figure 4). All measurements

1237 with a significant flow of sulfuric gas species ~~were measured~~ are from inside the ALTZ, while the flux of CO_2 was ~~also~~ high

1238 ~~outside~~well beyond the ALTZ.

1239 We, therefore, suggest the general color shift from reddish to gray to be related to ~~this~~a higher flux of sulfuric ~~gasses~~gases,

1240 promoting ~~a process of surficial~~ chemical leaching of iron oxides, via the reduction of the initially contained iron oxides to

1241 iron sulfates, which are ~~easily~~strongly soluble in rain or in condensing water vapor and are thus prone to rapid elution. Iron

1242 oxide content in our analyzed samples ranges from 1.5~~% (~~ % (sample A1) in the unaltered regime, to 1.1-1.4 % for A2/3

1243 samples, and to 0.3 for samples of the highly altered unit c (sample A4-6). There is a gradual reduction following the postulated

1244 alteration gradient, with the strongest changes ~~occurring on~~along the ~~ALT-AMT~~T3-T1 boundary (blue line in Figure 7). The

1245 1.5 % Fe_2O_3 for our rock sample of the unaltered regime is a rather low value and might be related to the fact that the sample

1246 was taken very close to the ALTZ boundary ~~and~~. It consists of > 50 % amorphous material. Fulignati et al. (1999), who provide

1247 a broader sampling database estimated Fe_2O_3 contents of unaltered ~~1988-1990~~1888-1890-eruptive products with 2.4~~6~~5-6.6~~5~~7

1248 %, which reduces to an average value of below 1 % in the ~~silic~~silicic-alteration regime (Fulignati et al., 1998~~;~~; Fulignati et al.,

1249 1999~~;~~; Boyce et al., 2007).

1250 ~~Evidence~~Further evidence for chemical leaching ~~can also be~~is found on the crater floor, where deposits form a colored layer

1251 resembling the color spectra widely observed on La Fossa, with bright reddish deposits close to the fumarole field resembling

1252 ~~classic~~fluvial patterns. We believe that the optically anomalous gray surface at Vulcano can generally be used to infer areas

1253 of present higher acid gas flux or former discharge of acid ~~gasses at even low flux rates.~~gases. Analyzing the broader area of

1254 the central crater region, we can infer multiple other areas where we observe similar ~~(~~changes of colorization that indicate

1255 similar argillic or strong silicic alteration effects at the surface. These are located on the southern inner crater, the outer crater

1256 rims, the 1988 landslide area (Madonia et al. 2019) and the northern flank towards Vulcano Porto. These zones of strong

1257 alteration are indicated in red in Figure 1B or Müller et al~~.,~~. (2021).

1258

5.2 Alteration gradients on local scales

1260 With average high SiO_2 contents of > 70 %, the sampled areas correspond to the large silicic alteration complex suggested by

1261 Fulignati et al. (1999), Azzarini et al. (2001), Boyce et al. (2007), and others. In our study, we show evidence for strong local

1262 alteration gradients and structurally important units, and spatially constrain them, ~~and~~thus we complement ~~detail to~~ earlier

1263 studies.

1264 Color shifts observed within the ALTZ associated with units a-g (brightness effects, hues of gray) are likely controlled by the

1265 degree of hydrothermal alteration, secondary mineral formation, and especially sulfur content in the respective surface samples.

1266 Coincident with characteristic changes in the surface coloration from Type 4 towards stronger bleached surfaces of Type 1,

1267 we observe a relative decrease of the initial mineral and element composition ~~by simultaneously increasing~~ and a simultaneous

1268 increase in sulfur content ~~(Figure 7)~~ for most of the obtained samples~~.~~ (Figure 7). While sulfur content in Type 1 surface ranges

20

from 6 to 31 %, for Type 2 it is already below 2 %, and for the unaltered fraction, it is below 0.2 %. We can, therefore, confirm a general link between alteration gradients~~,~~ sulfur contents, and surface brightness (or surface ~~Types~~types) in our remote sensing data (Figure 8).

An exception from this ~~systematic~~trend are sulfur contents of the Type 3 surface. Here we observe two distinct clusters~~,~~ (Figure 8), one with values below 0.5 % and one with extraordinarily high sulfur contents of 12 to > 60 %, both showing a similar surface coloration. All Type 3 samples with high sulfur contents are exclusively taken from LTZ. This strong discrepancy of sulfur content and surface coloration within the low-temperature zones suggests next to alteration gradients also surficial or shallow processes of mineral deposition and formation of sulfur-rich encrustations that form sealed surfaces, especially in the near field of fumaroles. The low temperatures observed within LTZ and the limited surface degassing highlight the efficiency of such sealing processes. So far we can not distinguish LTZ from Type 3 surfaces in our optical data (Figure 8). A distinction, however, would be beneficial as it would provide a method allowing for the precise spatial constraint of sealed surfaces from simple UAS-derived RGB imagery.

The intensity of optical and thermal effects and associated changes in mineralogical, ~~or~~and chemical composition ~~or~~, and degassing are not always equally significant. Although the general shift from unaltered surface to altered surface (ALTZ-boundary, shift reddish to gray) is a major criterion for the identification of degassing and alteration extent in our data, the associated changes in compositions are minor (Figure 9). The larger changes are observed within the ALTZ at the ~~ALT-AMT~~T3-T1 boundary~~.~~ (Figure 7). Here we observe a sudden decrease in the initial mineral and bulk geochemical composition and ~~equally~~an increasing sulfur content. We interpret the rather low changes at the transition from unaltered to altered at the ALTZ boundary to be related to rather weak or surficial alteration effects. The size of obtained samples was on the order of ~2000 cm² including the surficial part, but ~~also material up~~extends down to ca. 10 cm depth. This way, it was not possible to trace mineralogical or geochemical changes at the surface only. The samples obtained at the ~~ALT AMT~~T3-T1 boundary, on the other hand, show strong changes and reveal the general systematics of alteration effects, especially those samples taken in unit c, which might be considered one of the strongest alteration end members of the central crater region.

The identified surface patterns with respect to alteration gradients and structural units result from long-term evolution. However, some features may be subject to rapid changes. During the volcanic crisis in 2021, we observed, for instance, the formation of a new fumarole complex, which will locally change the composition, sulfur content, and surface type considered (cf. Figure 11), as is the case with sulfur deposits at the surface that can change quickly due to rainfall.

5.3 Heat budget - evidence for diffuse activity and surface sealing

~~Based~~Heat budgets ~~on the gained information we~~Vulcano have been studied earlier by e.g. ground-based surveys or satellite data (Chiodini et al., 2005; Harris et al., 2009), providing a range of estimates of thermal emissions (Mannini et al., 2019; Silvestri et al., 2019; Coppola et al., 2022). We compare our results to those using a remote sensing approach. Mannini et al.

1366 (2019) outlined a diffuse flux zone, which is comparable to the ALTZ defined by us. Further, they divided this zone into a

1367 diffuse flux zone and a vent flux zone and estimated the thermal radiation.

1368 We outlined the surface structure of the degassing and alteration system ~~of Vulcano~~ (simplified in Figure 10 and detailed views

1369 of the different alteration and thermal units in Appendix C) ~~and~~ based on the detection and classification of optical and thermal

1370 anomalies supported by additional mineralogical, geochemical, and degassing information, and spatially constrained high-

1371 temperature fumaroles (HTF), major diffuse active units ~~besides the HTF. To quantify~~ a-g, and Low-Temperature Zones (LTZ).

1372 We quantified their importance for the degassing and alteration system, ~~we weigh them based on a comparison of~~ by calculating

1373 their thermal energy release ~~(~~ according to the Boltzmann Law (Eq2 and Figure 10) for both, ~~the contribution of~~ anomalies

1374 with T ~~>~~ > 22°C, and identified units based on a spatial constraint, also including values >< 22°C. Therefore our identified

1375 structure differs from the vent flux and diffuse flux zone shown by Mannini et al. (2019).

1376 High-temperature fumaroles ~~of the upper fumarole field~~ in our study have ~~high~~ average radiant exitance values of 82 W/m² but

1377 can only account for 28 % of the total emitted thermal energy (calculations based on pixels with T ~~>~~ > 22°C and a corrected

1378 background of T ~~=16.71°C). The rest of the thermal energy is released by the diffuse features described above.~~ = 16.71°C).

1379 Note that when considering pixels with T > 40°C (as outlined by red patches in Figure 4D) the cumulative radiation of HTF

1380 would decrease to 0.2 MW only and the radiant exitance would increase to 242 W/m². The rest is released by the diffuse

1381 degassing part of the system. Although a direct comparison may be difficult, due to different outlines chosen for the respective

1382 flux zones, different sensor systems, and different background correction values, our cumulative radiation (Rcum in Figure

1383 10) for the HTF is comparable to those of Mannini et al. (2019). These authors suggested a vent zone heat flux of 0.35-0.96

1384 MW. Our estimate was ~1 MW, of which 0.5 MW are contributed by the high-temperature fumarole vents and 0.52 MW by

1385 unit c. This is also in accordance with the findings of Coppola et al. (2022), who estimate a similar vent zone flux from VIIRS

1386 imaging bands.

1387 ~~Next~~ However, the contribution of the diffuse thermal regime approximated by us is lower compared to ~~the HTF,~~ estimates in

1388 other studies (e.g Mannini et al., 2019), which place the contribution of the diffuse flux zone (comparable to our ALTZ) on

1389 the order of 90 % of the total flux. This is likely related to the fact that we did not estimate the flux of the ALTZ in total, but

1390 of multiple larger anomaly units within the ALTZ that have apparent structural importance for the degassing system. ~~This~~

1391 ~~becomes evident when analyzing the~~ and contribute ~50 % to the total flux. For future studies, a distinction into 3 different

1392 thermal regimes, a vent flux / high-temperature fumarole zone, a diffuse active units ~~for their~~ (like a-g shown in this study),

1393 and a broader low-temperature anomaly field (diffuse flux zone/ ALTZ) may be recommended to better resolve close range

1394 thermal-infrared remote sensing information with data from satellite-based studies.

1395 Regarding the heat budget estimated by us, the most dominant diffuse unit in terms of thermal energy release ~~(Figure 10).~~

1396 ~~The second important unit~~ is unit c. It has the second-highest average radiant exitance of 76 W/m² ~~but~~ and exceeds ~~the~~

1397 ~~cumulative radiant flux of HTF with a contribution to the total thermal radiation of~~. with 29 ~~%. Although it is~~% of the total

1398 thermal radiation, the cumulative radiation of the HTF. Unit c is not only a highly altered complex with ~~a strongly~~ the strongest

22

bleached surface and increased surface temperatures, there is also a discrepancy to the current degassing activity. Relative gas flux values measured within unit c are lower than observed for units a and b, for instance. This phenomenon might be a consequence of the ~~dynamics of hydrothermal alteration and indicate~~ permeability reduction or sealing processes due to the more advanced ~~state of~~hydrothermal alteration ~~like proposed by~~(cf. Heap et al.~~,~~. 2019~~.~~). This ~~would be~~proposition is supported by ~~a strong variability~~the strongest changes in mineralogical and bulk geochemical composition ~~and associated remineralization or~~observed in our samples, implying mineral (re-)precipitation ~~observed in~~is a major process in this particular unit ~~c.~~.

Diffuse aureoles (unit a/b) on the eastern side of the fumarole field cover several thousand m² each, more than the area covered by HTF~~, and~~. The diffuse aureoles contribute ~~with~~ 6 to 7 ~~%, or about 25 % of the energy emitted by the HTF~~ % each, to the total thermal energy release. ~~Additionally, the~~, equivalent to 25 % of the energy emitted in the high-temperature zone (HTF + unit c). Their bleached surface, increased surface temperatures (Figure 4), and higher gas ~~flow~~flux values (Figure 6 E-G) highlight their importance for the ~~surficial~~surface gas-drainage capability. However, mineralogical and bulk-chemical data suggests that the degree of alteration is less in these units, compared to unit c. This observation suggests that these sections are younger and therefore less altered and highlights their importance for the present-day degassing system.

~~Unit~~Units d and e are large diffuse ~~features~~degasing domains of the western fumarole field of which unit d is a part of the thermal aureole surrounding F0 and unit e is a ~~~200m~~200 m long branched anomaly, located rim parallel west of F0. Both have a similar contribution to the total thermal energy release ~~than~~as units a and b. Unit d is separated from ~~by~~ F0 by a low-temperature zone (LTZ3). The transition from ~~LTZ 3~~LTZ3 to unit d is sudden and accompanied by a temperature jump of ~ 20°C. The difference in the average temperature between unit d and LTZ3 is on the order of 5 °C. Also here we observe apparent surface sealing for the whole central fumarole field. Unit f, the northern section of the F0 aureole, and anomalies in the area north of the fumarole field (unit g) have a minor contribution.

~~LTZ1~~The Low-Temperature Zones (LTZ) 1-3 ~~separating~~, which separate diffuse aureoles from the HTF, have a Type 3 surface coloration, significantly lower temperatures, and radiant flux and exitance values than the neighboring aureole regions, ~~which~~what indicates processes of surface sealing. Indeed, no gas flux could ~~not~~ be constrained for the LTZ of the eastern fumarole field. From field observations and lab analyses (Figure 7), we constrained the LTZ as strong, sulfur-rich surface complexes ~~which are apparently~~that effectively ~~sealing~~seal the surface and ~~inhibiting~~inhibit gas ~~flow~~escape. The depth of these sealed complexes can not be constrained by our data, but we can ~~roughly constrain~~approximate the spatial extent. Considering only the 3 ~~LTZ~~LTZs of the central and eastern fumarole field, they ~~together~~ cover ~~at least an~~a total area of ~12000m², which is a significant fraction of the ALTZ. In other words, ~ 20 % of the surface of the ALTZ is apparently sealed ~~and~~, which forces lateral gas flow to the aureole regions. This was proven by observations during the 2021 volcanic crisis at La Fossa. While at fumarole sites and diffuse active units like units a and b showed ~~increasing~~an increase in mean temperatures and thermal energy release, the radiation within LTZ remained stable and low, highlighting the efficiency of ~~sealing processes.~~the proposed seal. This was observed for all central ~~LTZ~~LTZs, and is ~~exemplarily demonstrated by~~exemplified in a cross-section through the eastern fumarole field section (Figure 11D).

23

6 Conclusion

Our investigation of the fumarole field of the La Fossa cone allowed us to constrain the degassing and alteration structure, define major, so far undescribed units of activity, and quantify their importance for the degassing system, ~~highlighting in particular large diffuse degassing areas and localized surface sealing. Our experience from the study of the degassing and alteration system at Vulcano demonstrates that close-range remote sensing~~. Such high-resolution studies can greatly contribute to the understanding of structural architecture ~~or~~and add to our understanding of the intrinsic complexities of fumarole fields. ~~Such~~This realisation has implications for hydrothermal alteration studies, particularly for the identification of local variability, since local variations are frequently associated with mechanical, chemical, and permeability contrasts. The recognition of such contrasts is of use for an improved assessment of volcanic and degassing activity, but also possibly for other hazard aspects, such as e.g. stability assessments. We anticipate that combined remote sensing and petrological studies will prove beneficial for pre-site reconnaissance surveys for hydrothermal energy exploration, the detection of sampling locations for alteration-related studies ~~and sampling grid design~~, and, importantly, for ~~regular routine~~hazard monitoring of ~~hazardous~~ volcanic crater areas and associated risk assessment.

7 Tables

Table 1: Overview of the processed data sets that were used for the following analyses. From ~~The~~the optical data, an orthomosaic and DEM were generated covering 3.74 km² with pixel resolutions of 8.6 ~~x8~~ 8.6 to 17.3 x 17.3 cm. From the high altitude infrared overflight, an infrared mosaic was acquired covering 3.23 km² with ~~41.2~~38 x ~~41.2~~38 cm resolution. All data sets cover the complete central section of the La Fossa cone.

Data set	Acquisition date	Pixel resolution in cm	Coverage in km²	Point density in p/m²
2019 orthomosaic	14.11..2019	8.6 x 8.6	3.74	135.20
2019 DEM	14.11.2019	17.3 x 17.3	3.74	33.41
2018 IR mosaic	15.11.2018	~~41.2x 41.2~~38 x 38	3.23	5.64

24

8 Figures

A — La Fossa volcano

B — La Fossa Cone

38.41° N
38.405° N
38.4° N

14.9583° E   14.9625° E   14.9667° E   14.9708° E

250 m

X

hydrothermal alteration   crater rims

C — Orthomosaic of fumarole field

100 m

D — Field photo of fumarole field

A — La Fossa volcano

B — La Fossa Cone

38.41° N
38.405° N
38.4° N

14.9583° E   14.9625° E   14.9667° E   14.9708° E

250 m

X

hydrothermal alteration   crater rims

C — Orthomosaic of fumarole field

F0   F5AT
Fig. 2D   F11
Fig. 2A   Fig. 2B
FA   Fig. 2C
X
100 m

D — Field photo of fumarole field

F0   F5AT
F11
FA

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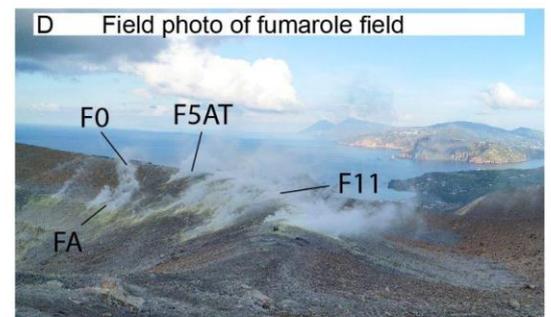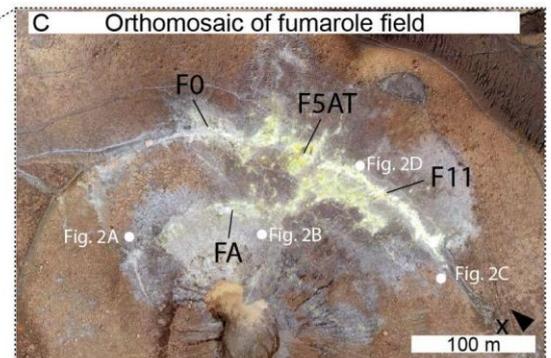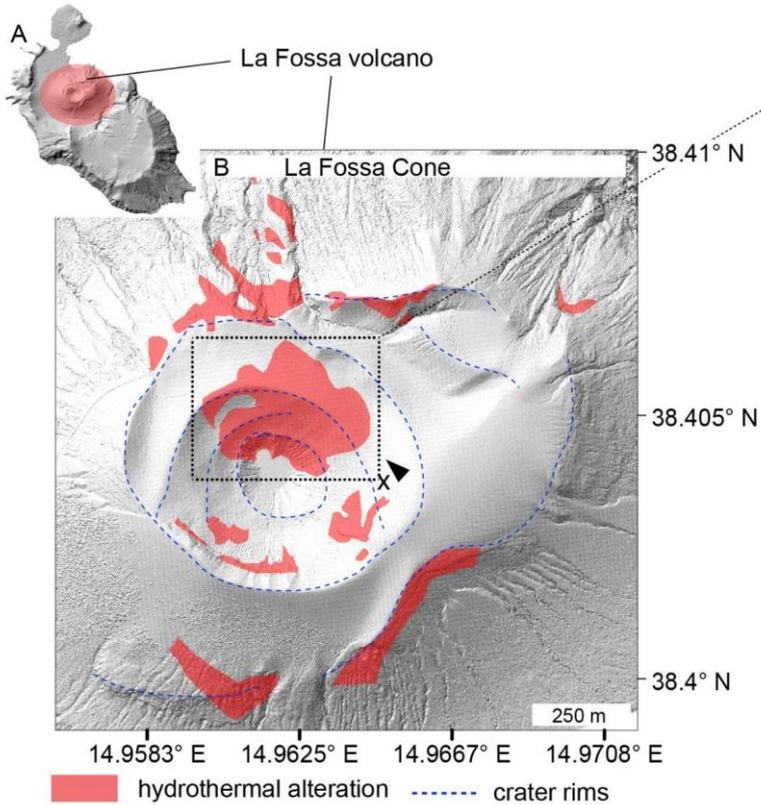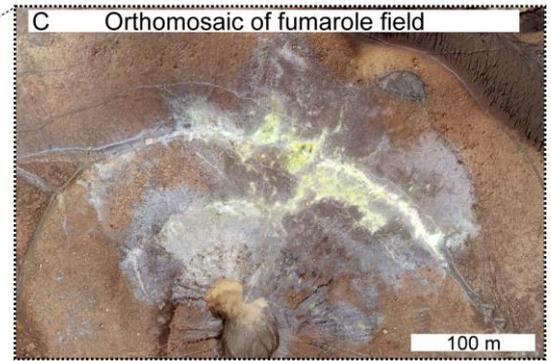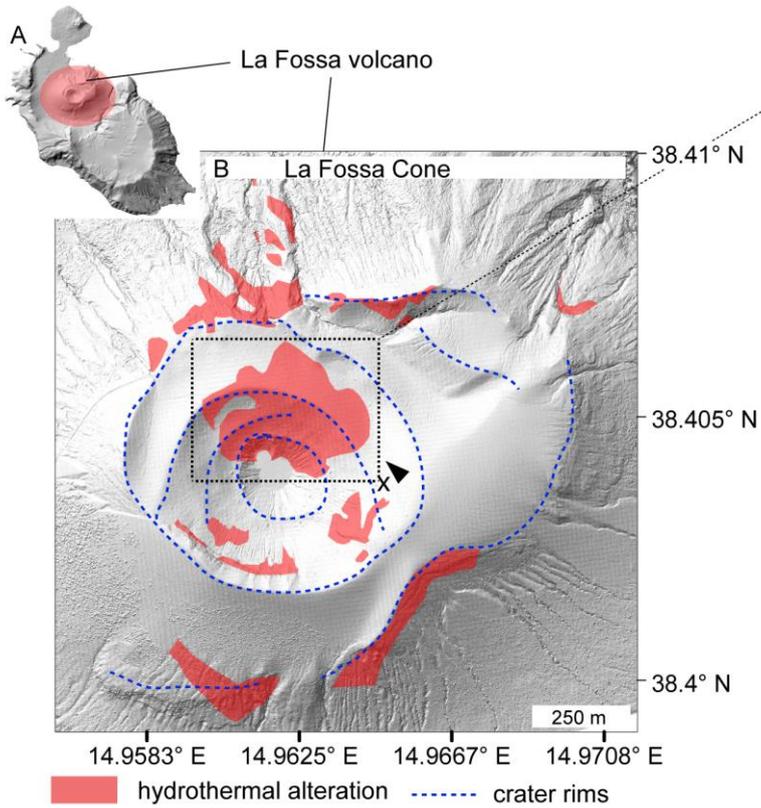
1539 Figure 1: Overview of the degassing sites at La Fossa cone, Vulcano Island (Italy). A) Vulcano Island as a shaded relief map.

1540 The red circle indicates the location of the La Fossa cone. B) Central summit ~~region~~area of the La Fossa Cone. Blue dashed

1541 lines ~~depict~~indicate crater ~~rimes of~~rims from different eruptive episodes. Areas of degassing and hydrothermal alteration are

1542 highlighted ~~by~~in red ~~patches after~~following Müller et al. (2021). The dashed box outlines the most prominent center of

1543 degassing and alteration, the high-temperature fumarole field. C) ~~The~~ Birds-eye view of the high-temperature fumarole field

1544 ~~from a birds-eye view.~~with prominent fumaroles F0, F5AT, F11 and FA marked. The locations of field photographs of Figure

1545 2 are indicated by white dots. D) Field ~~photograph over~~photo of the fumarole field. Location and viewing direction are

1546 indicated by an x and an arrow (B/C).

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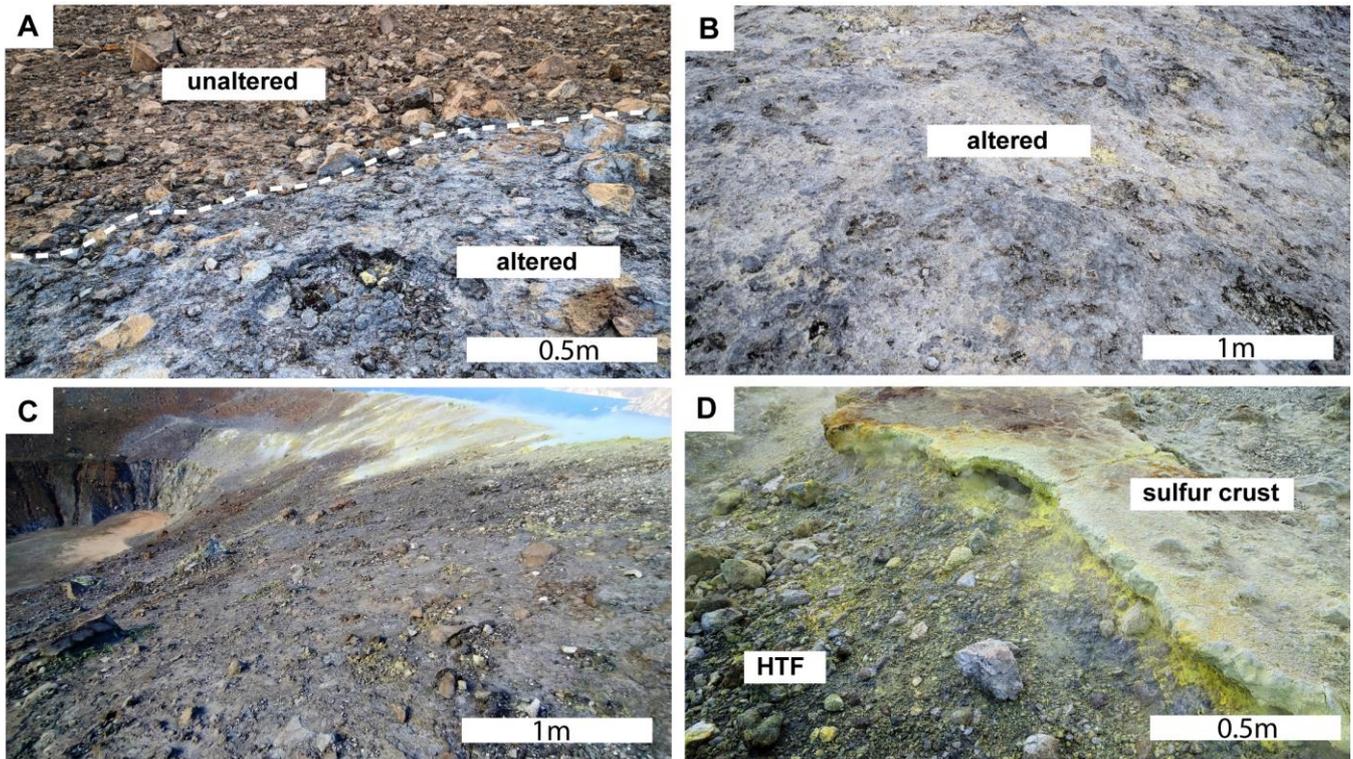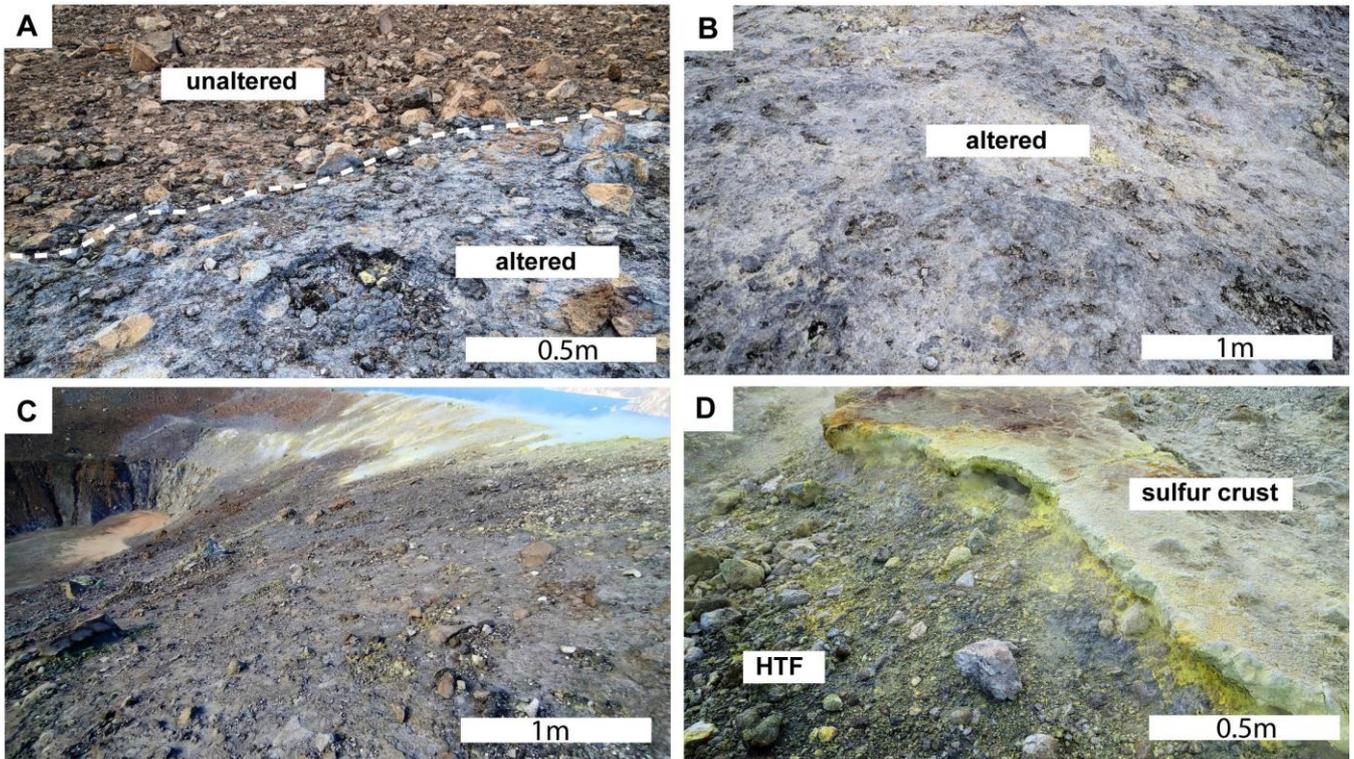
Figure 2. Different surface types and colorations in the La Fossa cone. A) Transition from unaltered to altered bleached surface. B) Intensely altered and bleached surface. C) View from the east onto sealed surfaces D) High-temperature fumarole (HTF) and deposited sulfur crust.

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optical   thermal infrared   CO2 / SO2 / H2S   XRD   XRF   thermal infrared

optical/thermal anomaly pattern

Degassing / alteration structure   ground-truthing

State of the degassing / alteration system   evolution during a volcanic crisis
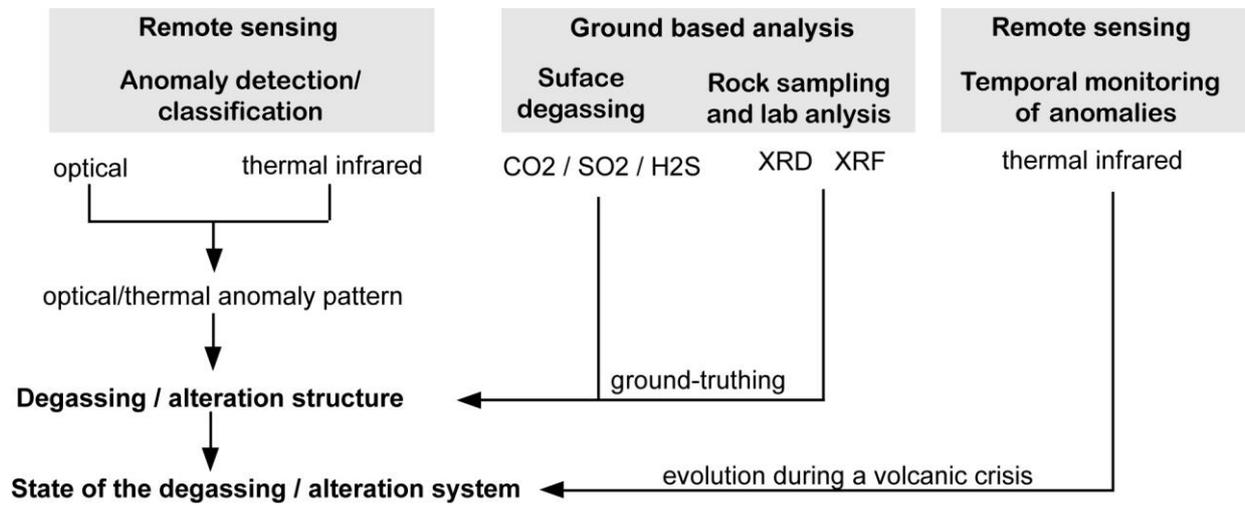
1590   ~~Figure 3: General workflow from anomaly detection from remote sensing data to ground truthing by mineralogical and~~

1591   ~~geochemical investigation.~~

1592

1593

1594

A Real-color orthomosiac of the fumarole field

ALTZ outline

unaltered

100 m

Type 4 | Type 3 | Type 2 | Type 1

B Alteration structure from image classification

ALTZ outline

ALTZ

unaltered

38.406° N
38.405° N
38.404° N

Type 4 | Type 3 | Type 2 | Type 1 | Sulfur

C Thermal infrared temperature map

ALTZ outline

15°C   60°C

14.959° E   14.961° E   14.962° E   14.964° E

D Thermal structure - thermally active surface

ALTZ outline

LTZ 3   LTZ 1
LTZ 2

HTF   diffuse thermal activity

38.406° N
38.404° N
38.405° N

14.959° E   14.961° E   14.962° E   14.964° E

Remote sensing	Ground based analysis		Remote sensing
Anomaly detection/ classification	Suface degassing	Rock sampling and lab analysis	Temporal monitoring of anomalies
Optical Thermal infrared	CO_2 / SO_2 / H_2S	XRD XRF	Thermal infrared

Anomaly pattern

Degassing / alteration structure

Ground-truthing

State of the degassing / alteration system

Evolution during a volcanic crisis

Figure 3: Overview of the general workflow used for this study. An anomaly detection from optical and thermal infrared

1613 remote sensing data allows us to reveal the anomaly pattern and infer the surface structure of the degassing and alteration
1614 system. To validate the observed structure, the remote sensing study was complemented by surface degassing measurements
1615 revealing the present-day degassing pattern, and by X-ray diffraction (XRD) and X-ray fluorescence (XRF) analysis of selected
1616 rock samples to prove different alteration units based on changes in mineralogical and bulk-chemical composition. Continuous
1617 monitoring by high-resolution thermal remote sensing data allows to record dynamics within the system and to draw
1618 conclusions about the general condition of the degassing/alteration units, e.g. with regard to alteration-related processes like
1619 surface sealing.

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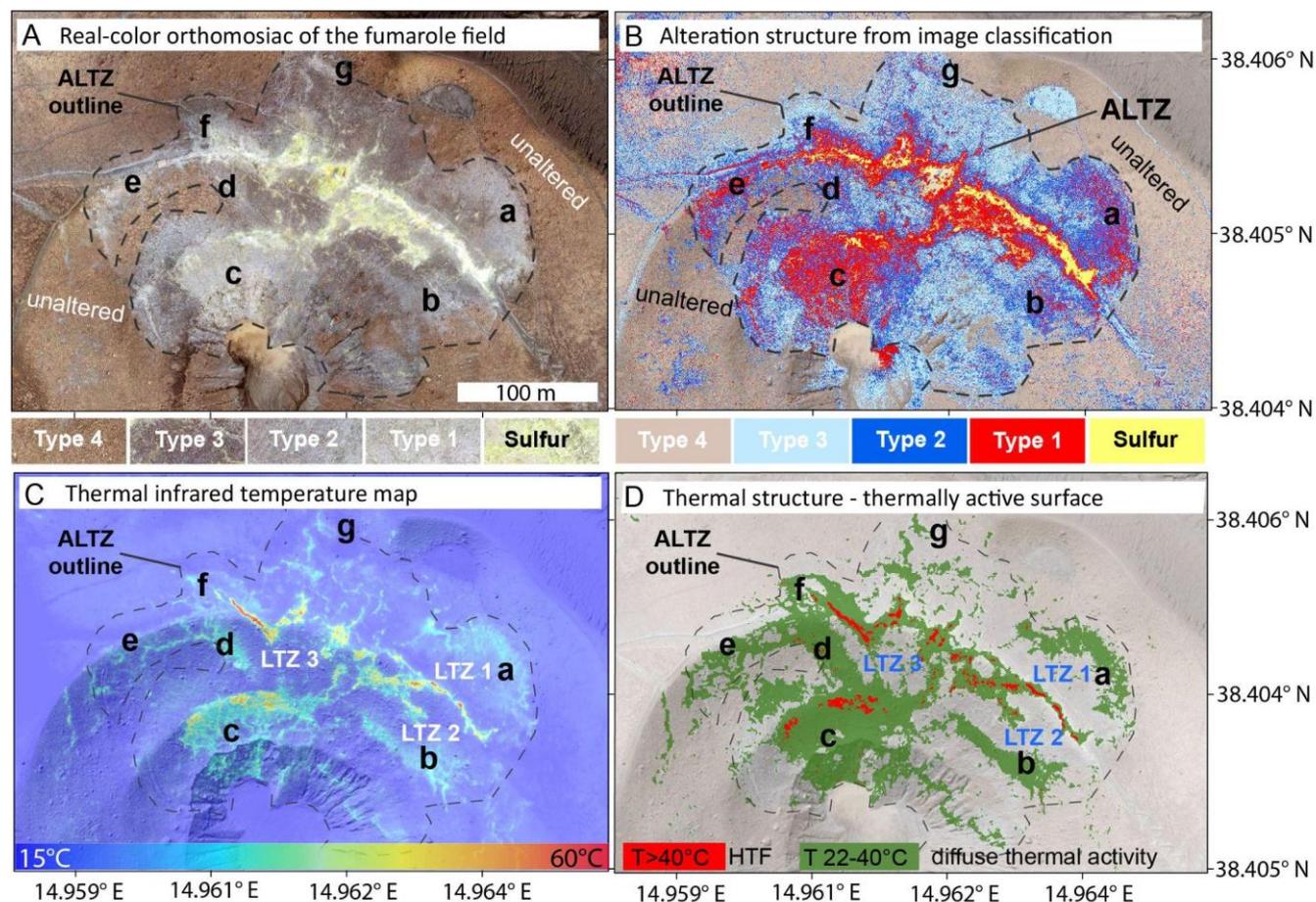
1623 Figure 4: Alteration structure of the La Fossa fumarole field. A) True color image of the high-temperature fumarole field with
1624 color samples of the surface types 1-4 and sulfur at the bottom of Fig. A. B) Alteration structure of the fumarole field as
1625 revealed by PCA and image classification, represented by the classified surface Typestypes 1-4. and sulfur at the bottom of
1626 Fig. B. C) Thermal infrared imagetemperature map of the fumarole field. D) Simplified thermal structure of the fumarole field

highlighting high-temperature fumarole location in red (T > 40 °C) and diffuse thermal activity in green. Labels (T = 22-40 °C). The dashed line labeled ALTZ outline demarks the boundary of visible optical effects at the surface and is referred to by us as ALTZ (Alteration Zone). The labels a-g representdemark notable large-scale anomaly units that can be observed in both, the alterationoptical data and the thermal data. LTZ 1-3 demark low-temperature zones that separate the high-temperature fumaroles and diffuse active units and cover significant parts of the central fumarole field. Note that the contrast of the background image has been reduced for highlighting in Subfigures B and D.
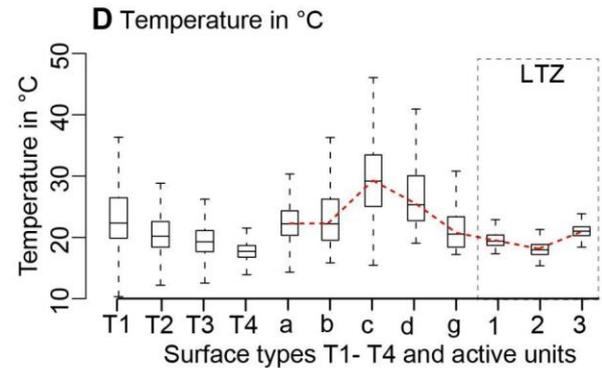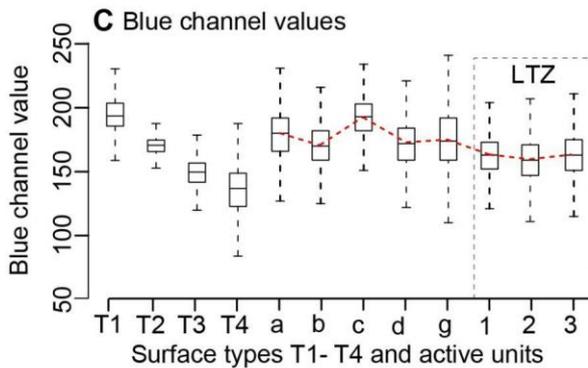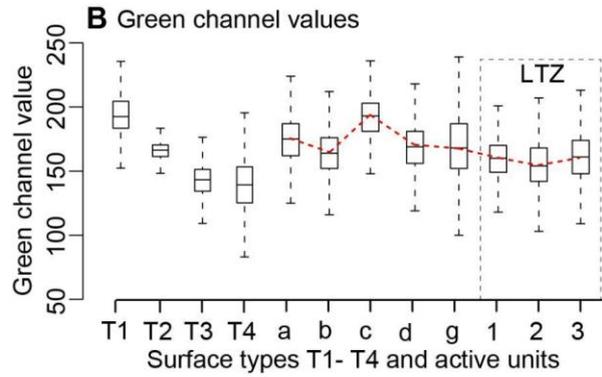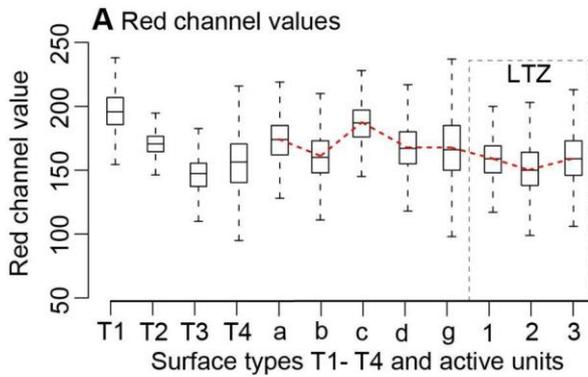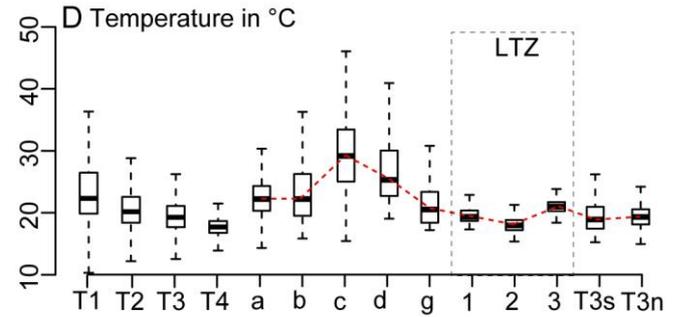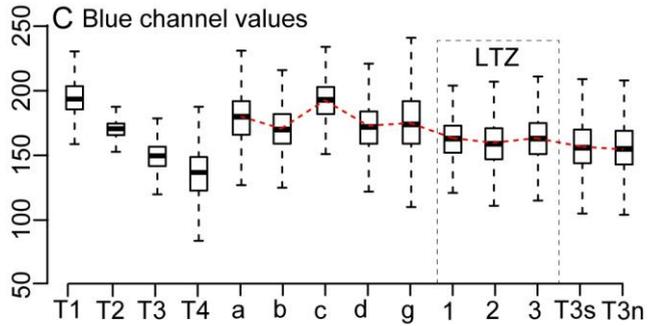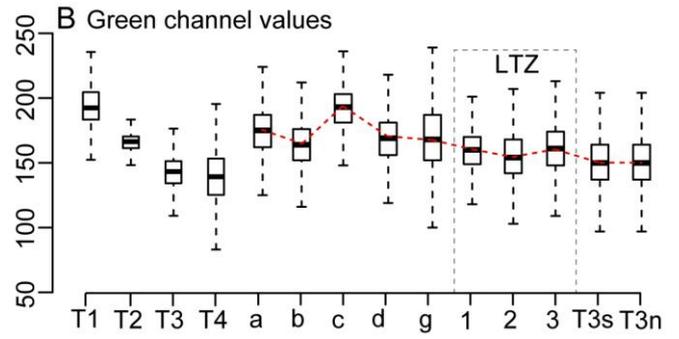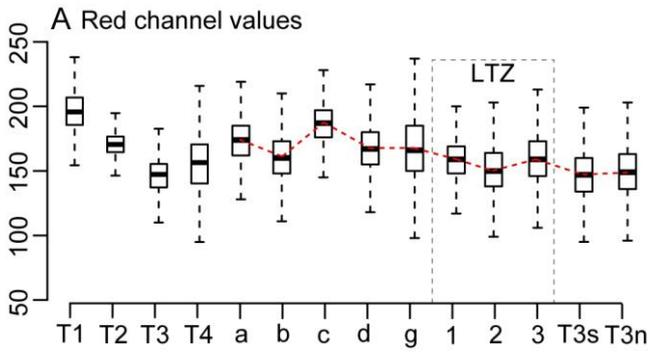
1644 Figure 5: ~~Color~~Boxplots of RGB color value- and temperature distributions observed for the different surface Types 1-4 (T1-

1652 T4), ~~selected areas~~identified active units a-g, and associated low-temperature zones LTZ1-3 ~~(location see~~. Surface types and

1653 locations of identified units are depicted in Figure 4B/D~~).~~. A) Red ~~color~~channel value distribution. B) Green ~~color~~channel

1654 value distribution. C) Blue ~~color~~channel value distribution. D) Temperature value distribution. Values are based on an analysis

1655 of 6.8 million pixels within the ALTZ. Both, the optical (Figure A-C) and thermal (Figure D) value distributions show

1656 similarities with generally decreasing values from the T1-T4 surface, a peak in unit c, and low values for LTZ1-3.

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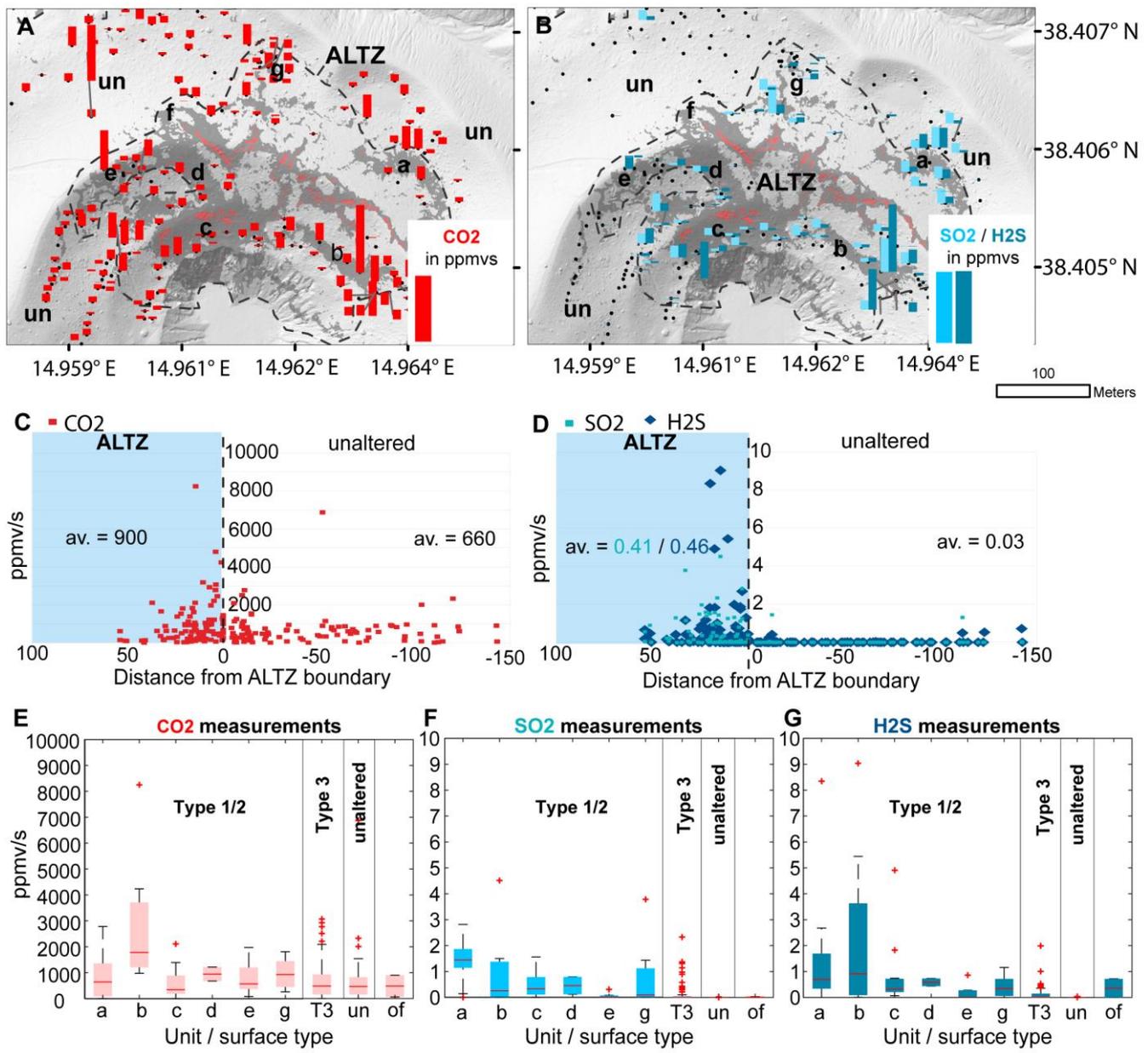
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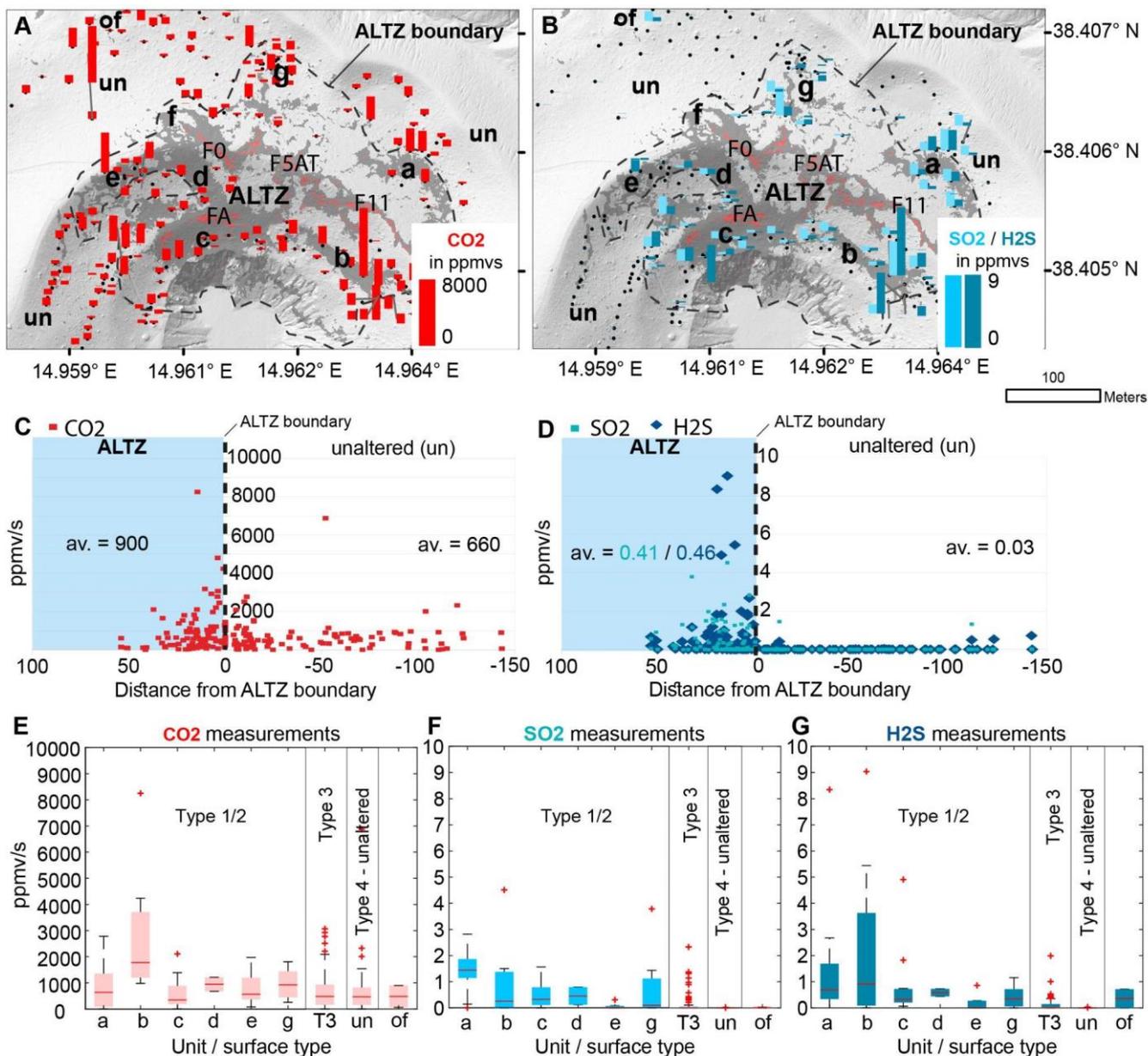
Figure 6: A/B) Spatial distribution and flux values for CO_2 (red bars in A)), SO_2 (light blue bars in B), and SO_2/H_2S (turquoise bars in B) in a map view. for 200 measurement points. Each bar represents a relative flux value at a measurement location. In case no flux was detectable, the respective location is marked with a black dot only. The dashed line highlights the ALTZ (Alteration Zone) boundary. Dark grey features in the background highlight the thermally active surface (compare Figure 2D). Labels F0, F5AT, F11, and FA mark prominent high-temperature fumaroles. The labels a-g mark notable large-scale anomaly units. C/D) Flux values within or outside the ALTZ are plotted by distance to the ALTZ boundary. (dashed line). Measurement

points within the ALTZ are represented by positive distances from the ALTZ boundary (highlighted by blue background) and measurements outside the ALTZ by negative distances (unaltered). A generally higher flux is observed within the ALTZ, but while CO_2 (C) is also abundant outside the ALTZ, significant SO_2 and H_2S fluxes were observed exclusively within the ALTZ, especially on the outer edges. E-G) Flux and associated with units a-g. The averaged flux values for (av) are depicted in the respective sections of C and D. E-G) Relative flux values of identified units (a-g,). Type 3 surface and(T3), the unaltered surface (un), and fumaroles on the northern rim at a distance (of) highlight the spatial variation of different gas species with high flux values for units a and b, lower flux values for e.g. unit c and generally lower flux of sulfuric gas species in the unaltered regime outside the ALTZ.

A

Legend

XRD Analysis
- Sanidine
- Cristobalite
- Sulfur

XRD Analysis — Transect A

A1	A2	A3	A4	A5	A6
13 / 87	14 / 86	13 / 87	20 / 18 / 62	72 / 25	40 / 60

ALT-AMT

Transect B

B1	B2	B3 (LTZ)
32 / 68	51 / 49	100

unaltered → Type 2/3 surface → Type 1 surface

Type 1 surface

B   XRF Analysis

Transect A — Transect B — Transect C

Legend:
- LOI
- S
- TiO2
- P2O5
- K2O
- Na2O
- CaO
- MgO
- MnO
- Fe2O3
- Al2O3
- SiO2

A1 | A2 | A3 | A4* | A5 | A6 | B1 | B2* | B3* | C1 | C2 | C3 | C4* | C5* | C6* | C7* | C8 | C9

ALTZ   ALT-AMT   LTZ   LTZ

A

Legend

XRD Analysis
- Sanidine
- Cristobalite
- Sulfur

Surface types
- Sulfur
- Type 1
- Type 2
- Type 3
- Type 4

ALTZ outline

T3-T1 boundary

Figure 7: Mineral and <u>bulk</u> chemical composition of <u>rock</u> samples along 3 transects A-C<u>,</u> crosscutting alteration gradients<u>,</u> and structural units. <u>A) Overview map with defined surface types 1-4, highlighting the area with visible optical changes at the surface, referred to as ALTZ (Alteration Zone, marked by a dashed line). The three transects A-C were placed so that they crosscut prominent units. Mineralogical compositions from XRD (X-ray diffraction) are depicted by circular plots at the bottom of Fig. A. B) Bulk chemical composition from XRF (X-ray fluorescence) analysis of transects A-C.</u> Transect A/B) With increasing alteration intensity we observe a relative decrease of the initial mineral phases sanidine and cristobalite whereas the sulfur content increases. Note that the mineral composition in this figure is normalized to 100 % non-amorphous minerals. In the chemical composition, we observe a significant decrease of Al_2O_3 and Fe_2O_3 but an increase of MnO, TiO_2, and S with increasing alteration, especially at the ~~ALT-AMT~~<u>Type3-Type1 (T3-T1)</u> boundary~~. At~~ <u>marked in light blue. For</u> transect C we observe a dominant increase of S <u>(</u>17<u>-</u> - 40~~%~~ <u>%)</u> for samples taken within the LTZ~~. Else than observed for the~~ <u>(low-temperature zone). Compared to</u> other transects, changes in Al_2O_3, Fe_2O_3, TiO_2, and MnO are less significant~~, even in the active units a and b.~~<u>.</u> For samples marked with an asterisk (*) ~~xrf~~<u>XRF</u> results are not available. <u>No XRD results are available for transect C.</u>
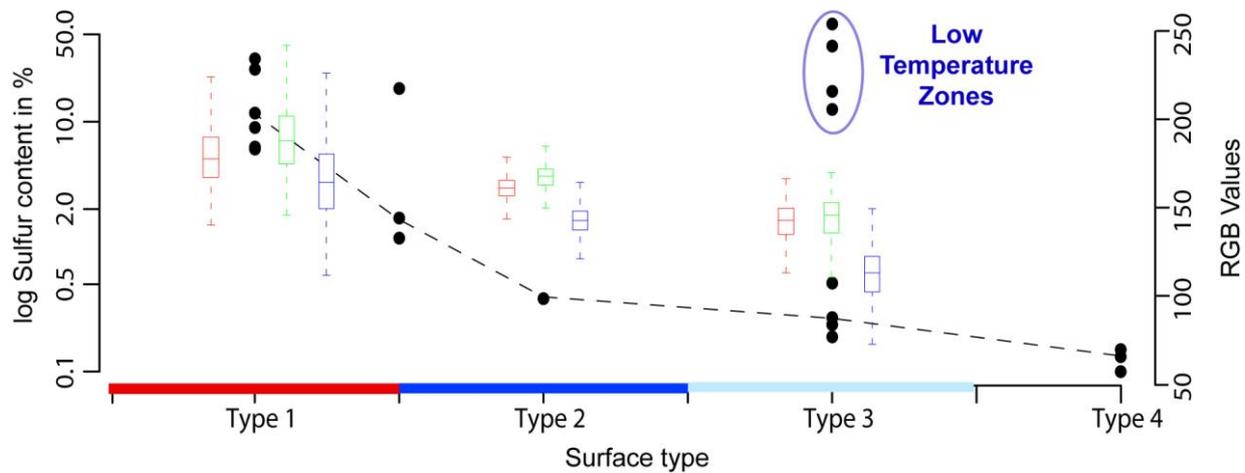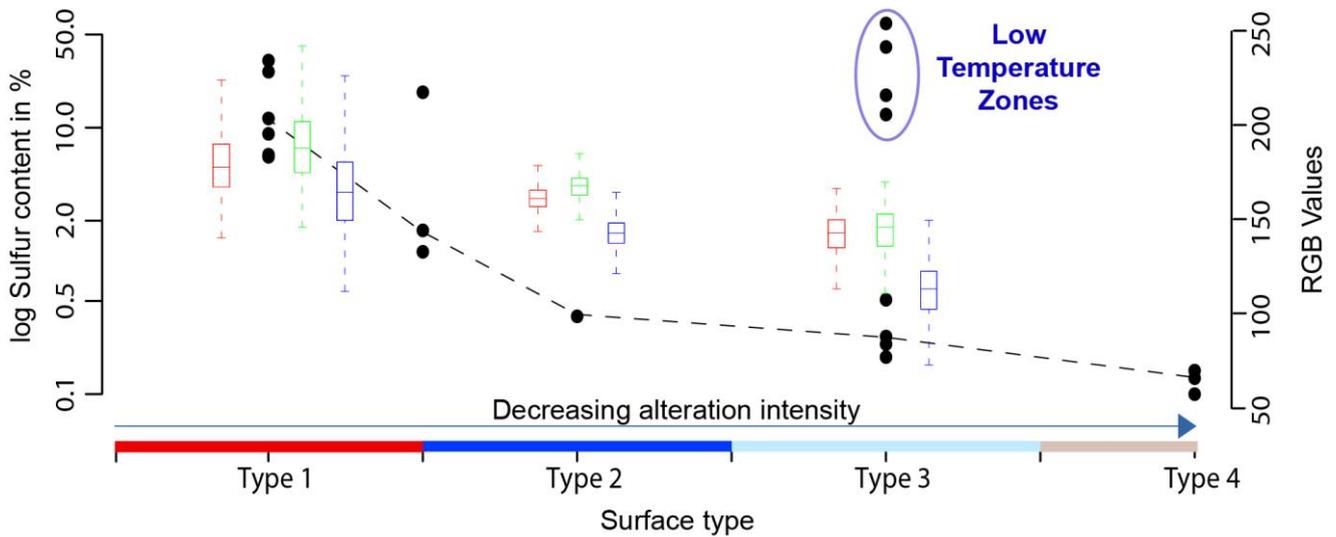
Figure 8: ~~Overview~~Relation of ~~the relation of~~ inferred surface type (T1-4) and sulfur content of rock samples ~~and brightness or inferred~~taken in the respective surface ~~Type~~T1-4. Black dots mark the sulfur contents of rock samples~~, and~~ and are shown on a log scale versus the ~~color coded box plots the respective value range in the RGB values.~~surface type from which the sample was taken, labeled by Type 1-4 on the x-axis and demarked with boxes using the same color code as throughout the manuscript. With decreasing alteration from Type 1 surface ~~Type from highest altered (to~~Type ~~1) to unaltered (Type 4), the measured sulfur contents~~ 4 surface we see a significant decrease~~.~~ of sulfur content from up to 100 % for Type 1 to < 1 % for Type 4 surface. The black dashed line illustrates this. An exemption is the Type 3 ~~surfaces~~surface where we observe two distinct clusters, one with low ~~S~~sulfur values and one with ~~extraordinarily high S values.~~ exceptionally high sulfur values. These high sulfur values belong to samples taken in the LTZ (low-temperature zones), which separate fumaroles from the larger diffuse active units a and b (compare Figure 4) for instance. These samples indicate that LTZ represent sulfur-rich crusts that block heat and gas flux from the surface. The colored boxplots show the distribution of RGB values for the respective surface Type 1-4, showing a similar trend of decreasing values. Red boxplots represent the red value, blue and green the respective blue and green channel values of the image. The coincidence between both indicates a direct relation or control of sulfur onto the surface colorization.
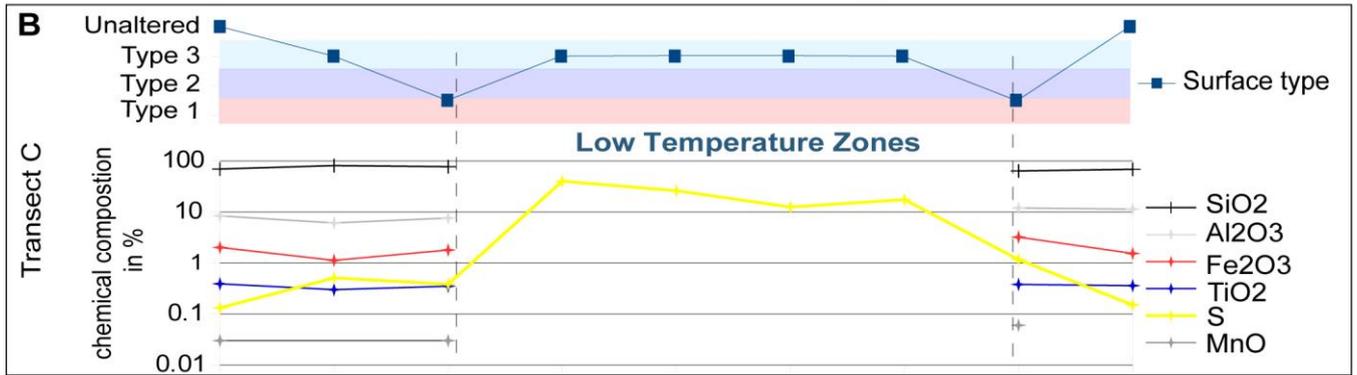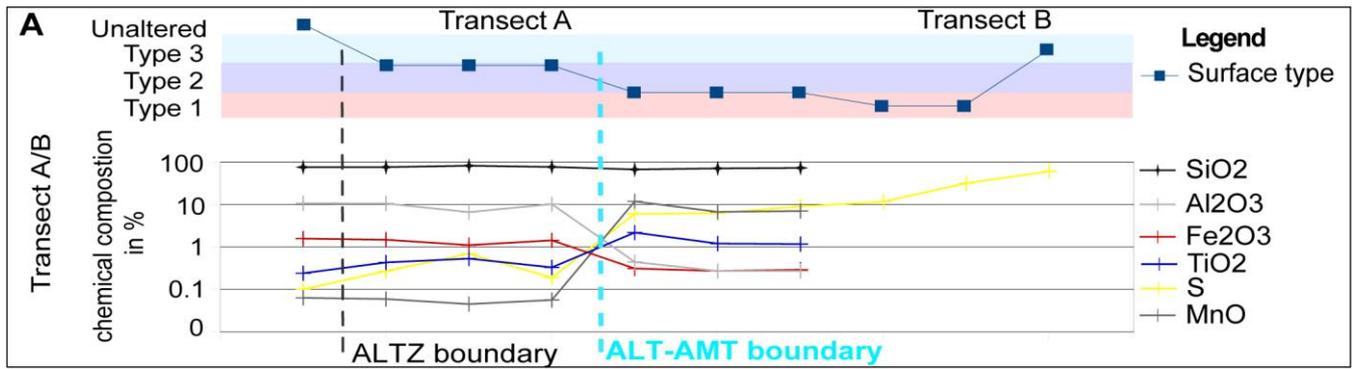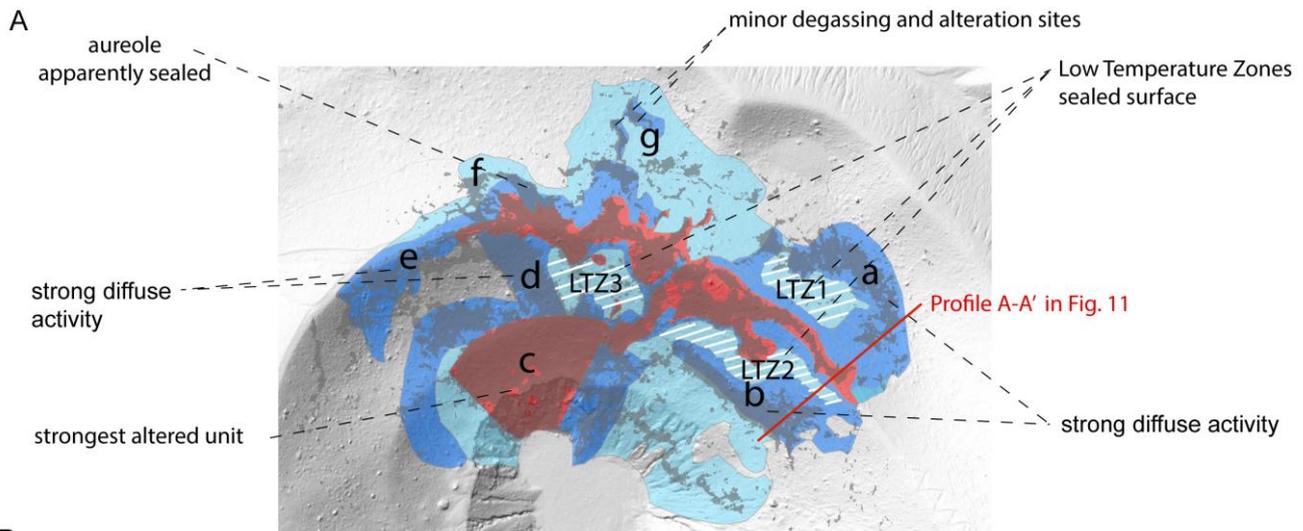
1774
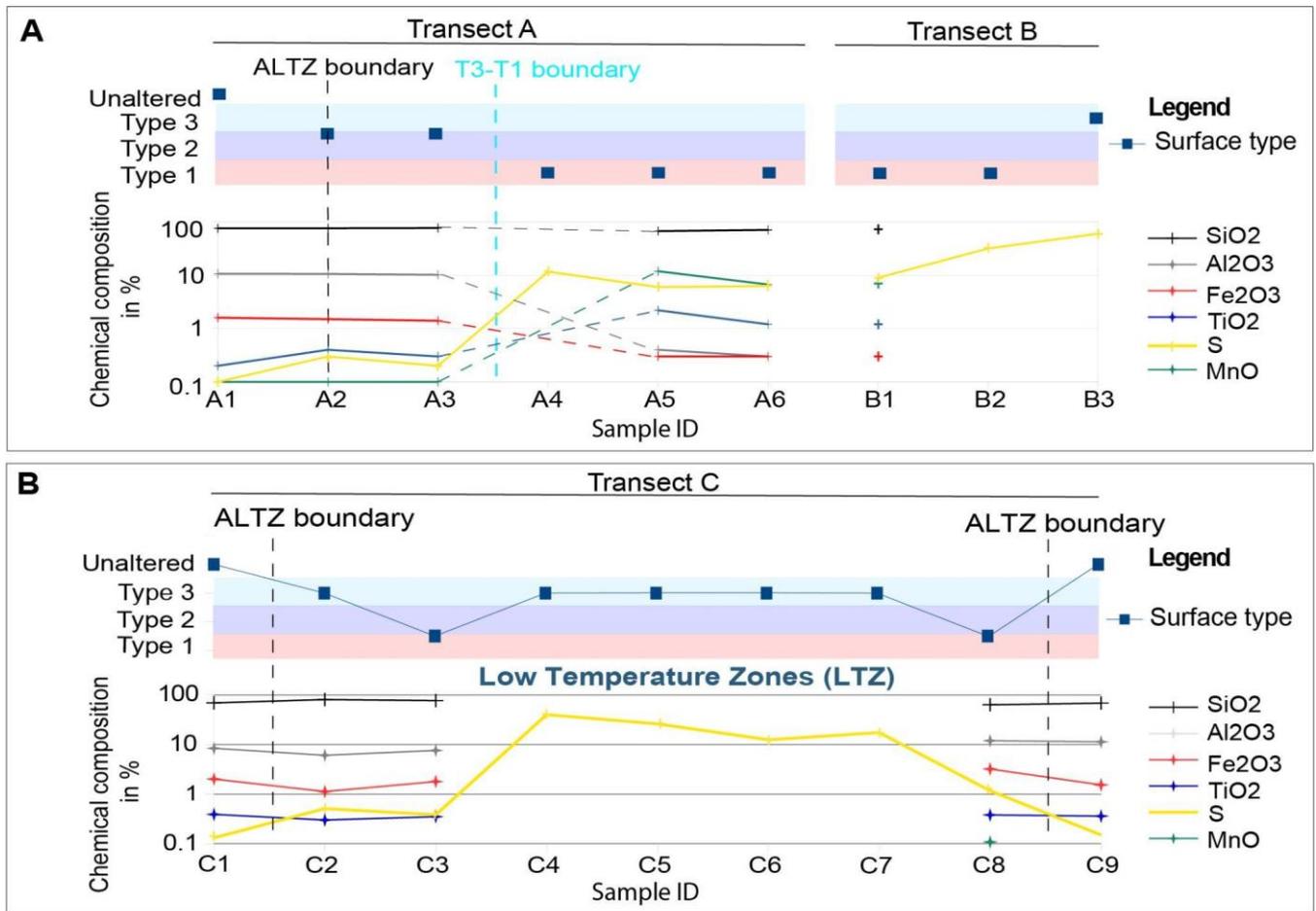
Figure 9: ~~Geochemical changes~~Changes of surface type and bulk-chemical composition observed along ~~transect~~transects A~~-~~, B, and C. Locations for the transects and sample ID are shown in Figure 7. A) With increasing alteration from Type 4 to Type 1 surface we observe a reduction of ~~-~~Fe_2O_3 and Al_2O_3 and an increase in ~~S. Strongest~~Sulfur. While changes observed at the ALTZ boundary (black dashed line) are only minor, strong changes are observed at the ~~ALT-AMT boundary.~~Type 3-Type 1 boundary (T3-T1, blue dashed line). Sulfur contents in transect B were so high that XRF results were only available for sample B1. B) Changes observed in the eastern fumarole field along transect C are less significant, with the exception of ~~extraordinary~~extraordinarily high sulfur content for Type 3 samples~~, which represent~~ collected in the LTZ.

A

aureole apparently sealed

minor degassing and alteration sites

Low Temperature Zones sealed surface

g

f

strong diffuse activity

e   d   LTZ3   LTZ1   a

Profile A-A' in Fig. 11

c   LTZ2   b

strongest altered unit

strong diffuse activity

B

% of total thermal radiation

30
25
20
15
10
5
0

◆ T>22 °C
■ T>16.7 °C

LTZ

HTF a b c d e f g 1 2 3 T3s

unit

C

Rcum in MW

0.6
0.5
0.4
0.3
0.2
0.1
0

c   HTF

a e
T3s f g   b d

LTZ 2 3 1

30 40 50 60 70 80

RE in W/sqm

A

Aureole, apparently sealed

Minor degassing and alteration sites

Low Temperature Zones, sealed surface

g

f

e   d   LTZ3   LTZ1   a

Strong diffuse activity

Profile A-A' in Fig. 11

c   LTZ2   b

Strongest altered unit

Strong diffuse activity

Type 1 surface
Type 2 surface
Type 3 surface

B

f total thermal radiation

30
25
20
15
10
5

◆ T>22 °C
■ T<16.7 °C

LTZ

C

Rcum in MW

0.6
0.5
0.4
0.3
0.2
0.1

c   HTF

Type 1 surface

a e   b d   Type 2 surface
f g

1806 Figure 10: Anatomy of the fumarole field. A) Simplified structure of the fumarole field highlighting surface types and
1807 structural units of increased diffuse activity (a-g) or areas of apparent surface sealing (LTZLTZ1-3 marked by white lines). B)
1808 Contribution to the total thermal radiation in % to the total radiation for anomaliesHTF (high-temperature fumaroles), units a-
1809 g, and LTZ1-3 (low-temperature zones) considering pixels with T> < 22°C (blue) and for identified units based on a spatial
1810 constraint, also including and pixel temperatures <> 22 °C. (orange). C) Radiant exitance (RE) in W/m² and cumulative
1811 radiation (Rcum) in MW. Rcum is the cumulated background corrected radiant exitance (Equation 2 in the method section) of
1812 all pixels associated with the respective active unit. Note that for RC and contribution to the total thermal radiation Rcum only
1813 anomaliespixels with T> > 22°C were used. We can clearly distinguish different thermal regimes that are also coincident with
1814 surface types identified in the optical data.
1815
1816

A

LTZ2 LTZ1

b a

B

A A'

C

sealed surface **LTZ2** **HTF** sealed surface **LTZ1**

permeable zone **b** permeable zone **a**

permeability reuction?

forced lateral gas flow?

D

A A'

Radiant density in KW/sqm

1.2 1 0.8 0.6 0.4 0.2 0

new fumarole complex in2021

permeable zone impermeable zone impermeable zone impermeable zone permeable zone

thermal aureole unit b LTZ2 HTF LTZ1 LTZ1 thermal aureole unit a

15/11/2018
20/09/2021
20/10/2021
18/01/2022
14/11/2022

A

LTZ2 LTZ1

b a

60°C

20°C

B

A A'

Type 1
Type 2
Type 3

C

Sealed surface **LTZ2** **HTF** Sealed surface **LTZ1**

Permeable zone **b** Permeable zone **a**

Permeability reduction?

Forced lateral gas flow?

D

A A'

iant exitance in kW/m²

1.2 1.0 0.8 0.6 0.4 0.2

New fumarole complex in 2021

Permeable zone Impermeable zone Impermeable zone Impermeable zone Permeable zone

15/11/2018
20/09/2021
20/10/2021
18/01/2022
14/11/2022

1832   Figure 11: ~~Crossection~~Cross Section of the eastern fumarole field along Profile A-A' (Fig.10) highlighting the structural setup

1833   from high-temperature fumaroles in the center to LTZ and diffuse aureoles at a distance. A) Thermal structure along the cross-

1834   section. B) Alteration structure along the cross-section. C) Schematic sketch along cross-section A-A', highlighting the

1835   central LTZ that might be controlled by surface sealing processes or deeper effects of permeability reduction in the vicinity to

1836   the high-temperature fumaroles due to long-term gas-rock interaction and alteration processes. D) Evolution of thermal

1837   radiation values during a volcanic crisis. While thermal radiation at fumaroles and aureoles increased, radiation values of LTZ

1838   ~~remain~~remained unchanged, therefore highlighting the efficiency of surface sealing.

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9 Appendices:

Appendix A: RGB value distribution of defined surface types 1-3 within the ALTZ
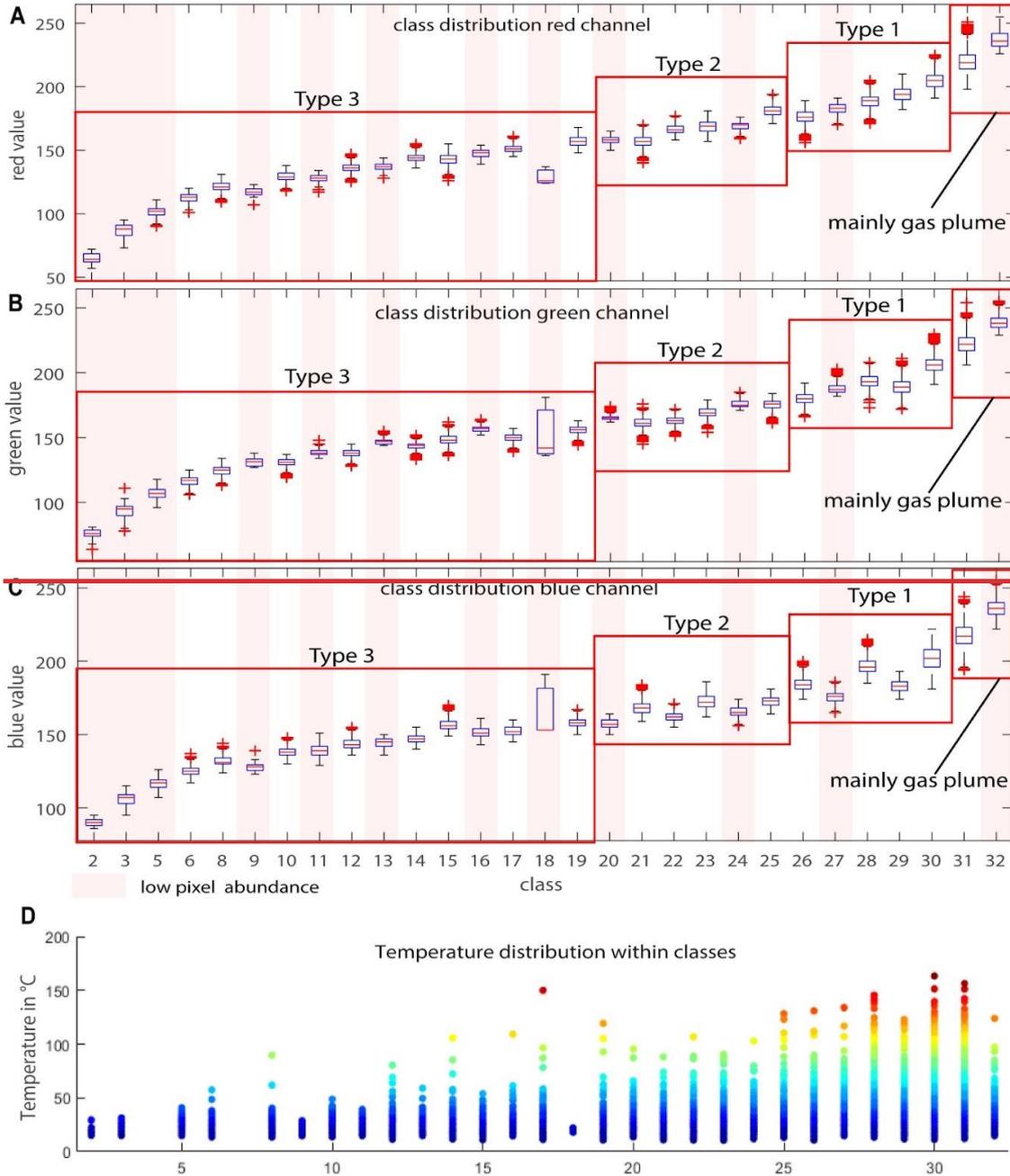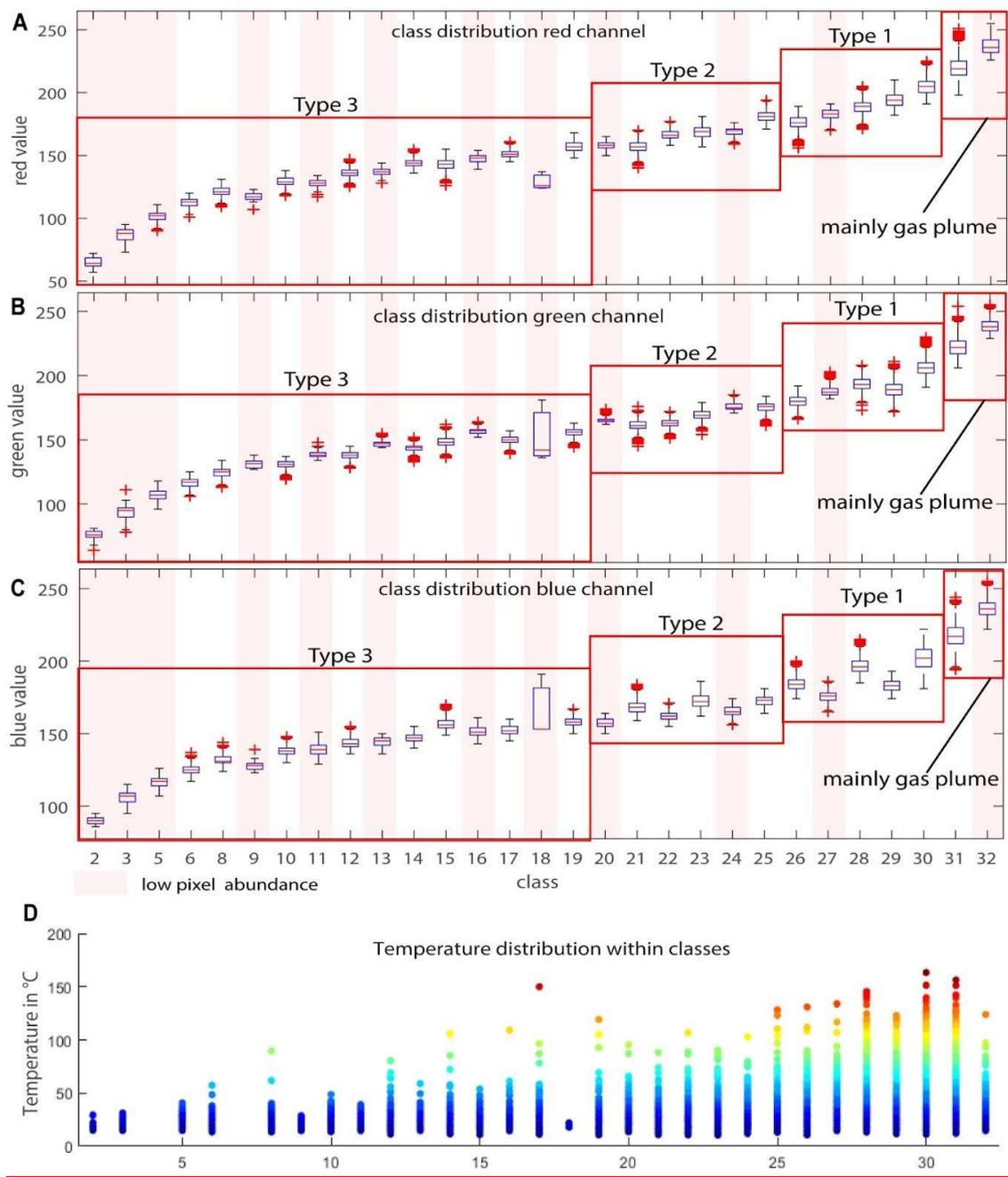
Figure A1: Boxplots of RGB value distribution for the defined surface Types 1-3. Classes (unsupervised classification 32 classes) marked with the transparent red bar only have minor pixel abundances. Red boxes depict the spectral range of Type 1-3 surfaces. Class 31 and 32 are mainly associated with the fumarole steam plume.

1877

Appendix B: Gas measurement procedure - simplified accumulation chamber approach
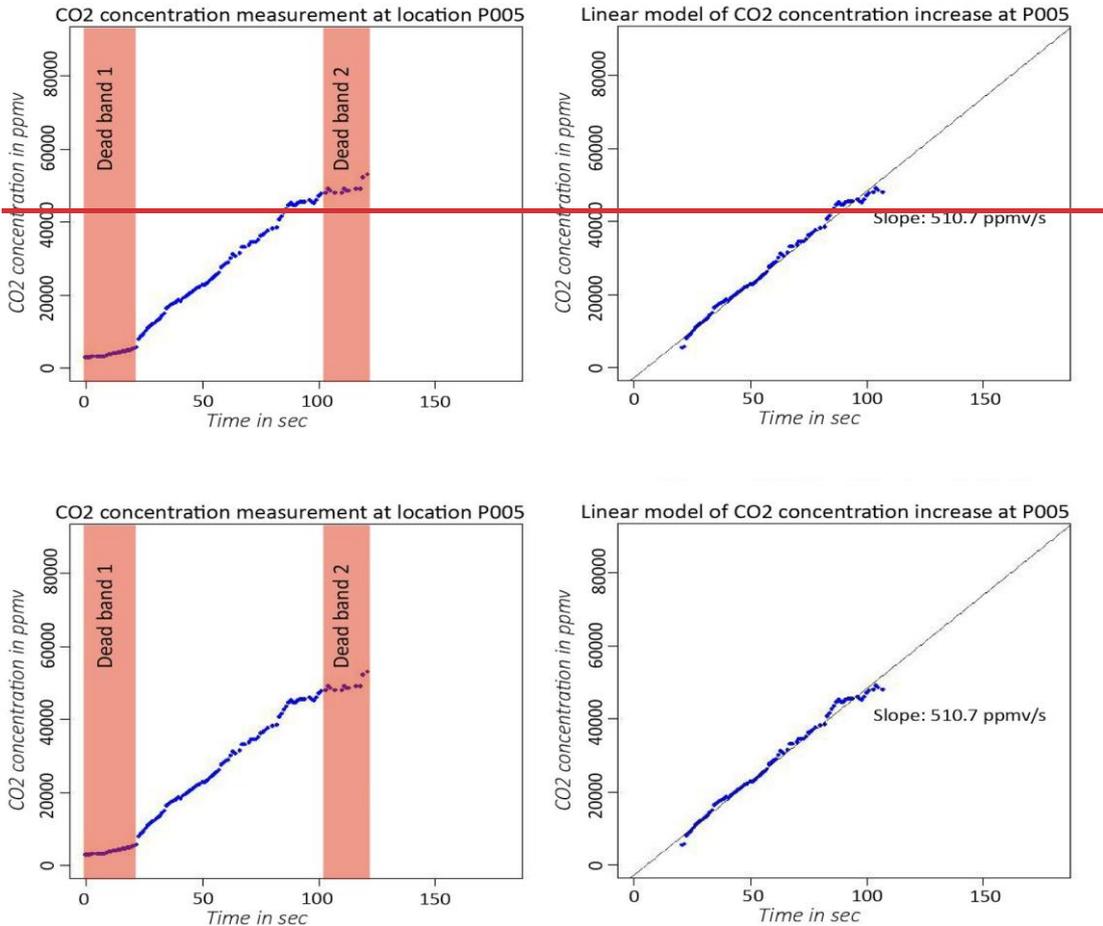
1879

1880

Figure B1: CO_2 measurement at location P005, here shown representative for all measurement points. Dead bands at the beginning and end of the measurement were removed and the intensity of gas flux was characterized by linear regression through the constantly ascending part of the graph. The slopes of the linear model allow a relative comparison of single measurement points.

1885

To compare the observations from remote sensing to present-day surface degassing, measurement campaigns were performed in September 2021 and November 2022. The surface degassing was measured at 200 points within the northern part of the la fossa cone (Figure 6 in the main manuscript), in a simplified multi-gas accumulation chamber approach.

The simplified accumulation chamber consists of the measurement unit, a Dräger Xam 8000, coupled to a 10.3 cm diameter and 16.5 cm long plastic chamber by a 116 cm long tube with an inner diameter of 0.5 cm, resembling a simplified

accumulation chamber. The plastic chamber has a volume of 1374.8 cm³, and the tube has a volume of 91.1 cm³, so that the total system volume is 1465.934 cm³. The pumping rate is 0.35l per minute. The plastic chamber was equipped with an open valve which was a necessity as the Dräger is an actively pumping system. Therefore, concentration increases in the chamber can be considered as surface flow and as independent from pumping effects. The Measurement unit is protected by a preceding 2µm filter, preventing dust and vapor to enterfrom entering the unit. Note that we use Flux values in this study only for relative comparison and detection of the spatial variability of certain gas species and flows. A precise flux estimate is beyond the scope of this publication and can not be constrained as we did not measure gas temperatures and humidity at sampling locations.

The measurement unit, a Dräger XAM 8000 handheld Multigas device was equipped with 6 sensors measuring CO_2, CH_4, SO_2, H_2S, H_2, and O_2 simultaneously. The relevant species for this work are CO_2, SO_2, and H_2S, therefore only these will be considered in detail. The CO_2 sensor is a Non-Dispersive Infrared (NDIR) sensor. NDIR sensors use the absorption characteristics of CO_2 at ~ 4 µm, which leads to a concentration-dependent amplitude loss of the internally emitted IR light. The sensor has a detection threshold of 0.01 vol% CO_2 and is calibrated for measuring CO_2 in a range of 0-5 vol % at a resolution of 50 ppm under normal (-20-50-°C, 10-95 % RH, and 700-1300 hPa) atmospheric conditions. The response rate is < 10 sec for reaching T50- and < 15 sec for reaching T90 concentrations. The H_2S sensor is an electrochemical sensor with a detection limit of 0.4 ppm and a resolution of 0.1 ppm, measuring in a range of 0-100 ppm H_2S under normal atmospheric conditions. The response time for T90 values is >15 seconds and the accuracy of the measurement is +-5 % of the measured value. The SO_2 sensor is an electrochemical sensor with a detection limit of 0.1 ppm and a resolution of 0.1 ppm, measuring as well in a range of 0-100 ppm under atmospheric conditions. The response time for T90 values is < 15 seconds and the accuracy of the measurement is 2 % of the measured value. The NDIR CO_2 sensor is robust against cross-sensitivities. However, electrochemical sensors can be vulnerable to cross sensitivities (SO_2, H_2S, Cl_2), resulting in uncertainties of the measurement of a few percent of the measurement value.

The approach of combining the Dräger multigas with an accumulation chamber was developed and adapted as a consequence of uncertainties encountered in previous campaigns. The different sensors have slightly different reaction times for ascending gas concentrations and significantly different reaction times for descending gas concentrations. Comparing sensor readings directly therefore might lead to odd gas ratios. For that reason instead of the direct gas readings, we use the slope of the ascending gas concentration within the accumulation chamber to produce more reliable estimates of the surface flow.

For a relative comparison of degassing rates of the single measurement points, the gas data was plotted and the representative part of the graph, resembling a constantly ascending slope, was used to calculate the concentration increase by linear regression. Data points of the "Dead Bands" at the beginning and end of each graph were removed. In this way, we achieve a relative gas flux from soil that allows us to analyze spatial variations of gas flux throughout the study area. An overview of all gas measurement points will be given in Figure 6. The aim of the gas measurements was not to provide accurate flux estimates but to highlight and quantify the spatial variability of the surface flux of certain gas species.

Each measurement was performed under similar conditions. Locations were selected in a way that they represent similar surface conditions, considering a spatial distance to fumarolic vents and an unsealed surface, for instance. Measurement locations typically were small areas with a naturally "open surface", often embedded in broader areas of the sealed surface. Such spots typically can be identified by loose gravel on the surface and in case slightly different coloration. For the measurement, the surface was cleaned and gravel was removed to provide a flat contact surface. Then the measurement was started, and the plastic chamber was placed on the ground and sealed on the bottom with fine-grained material. The average measurement duration was 2 min. In case of very rapidly ascending SO_2 or H_2S gas concentrations, the chamber was removed from the ground before and the system was flooded with fresh air, to protect the sensors from critically high acid concentrations. This procedure was chosen to ensure a fresh air flooded chamber at the beginning of each measurement and to record the initial atmospheric gas concentration. Further, it allows better identification of the measurement start- and end-

1981 points within the respective data sets, as each data series has two dead bands, one at the beginning and one at the end. Figure
1982 B1 shows a typical graph of a CO_2 measurement, with the Dead-Band at the beginning and end of each measurement and the
1983 constant ascending graph, representing the gas concentration increase within the chamber. The "Dead Bands" represent parts
1984 of the measurement where the accumulation chamber was placed on the ground but not sealed yet, or removed from the soil
1985 at the end of the measurements. Dead Bands at the beginning of the measurement were typically on the order of 20- 30 s,

1986

Appendix C: Detail views on identified units
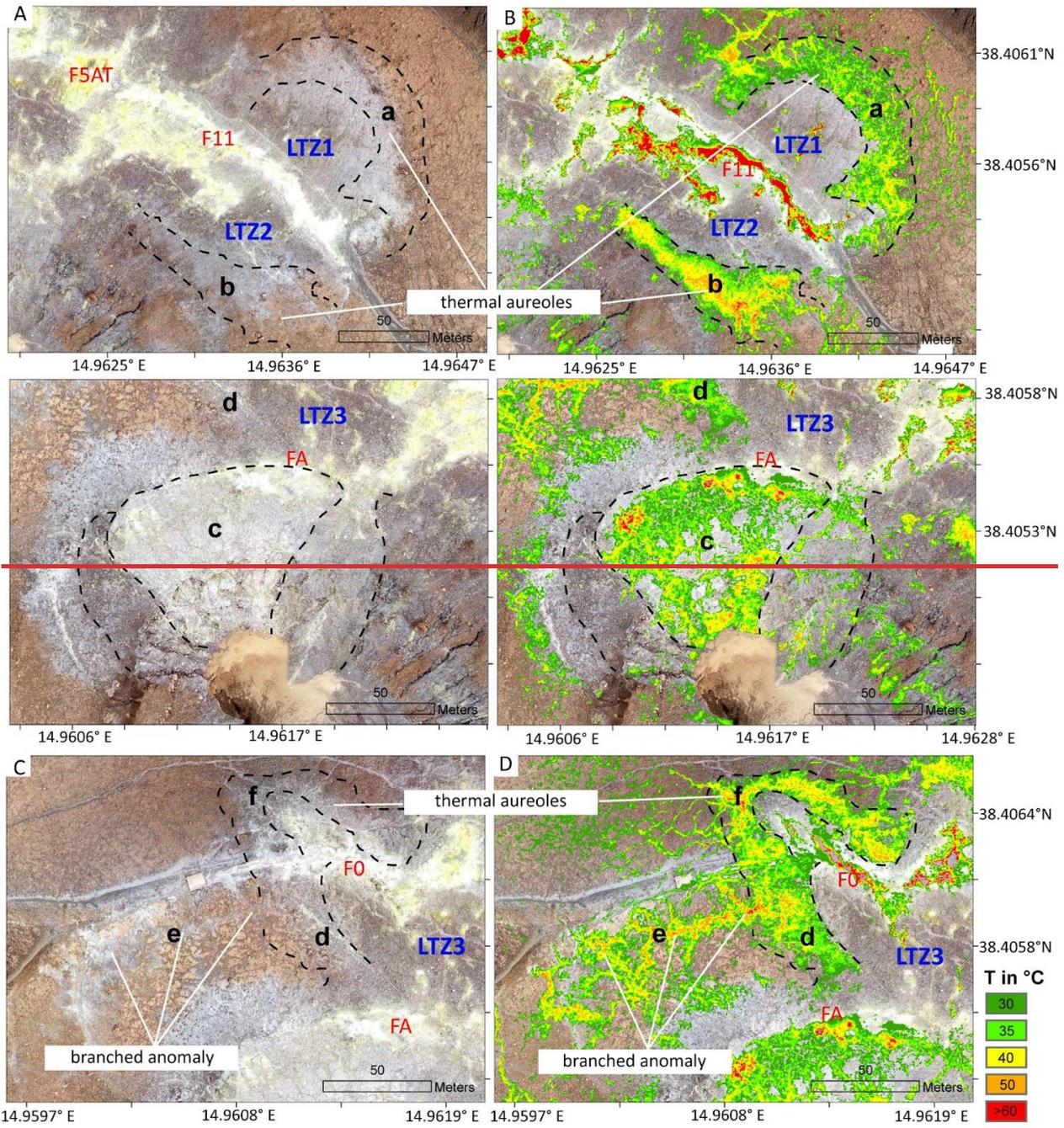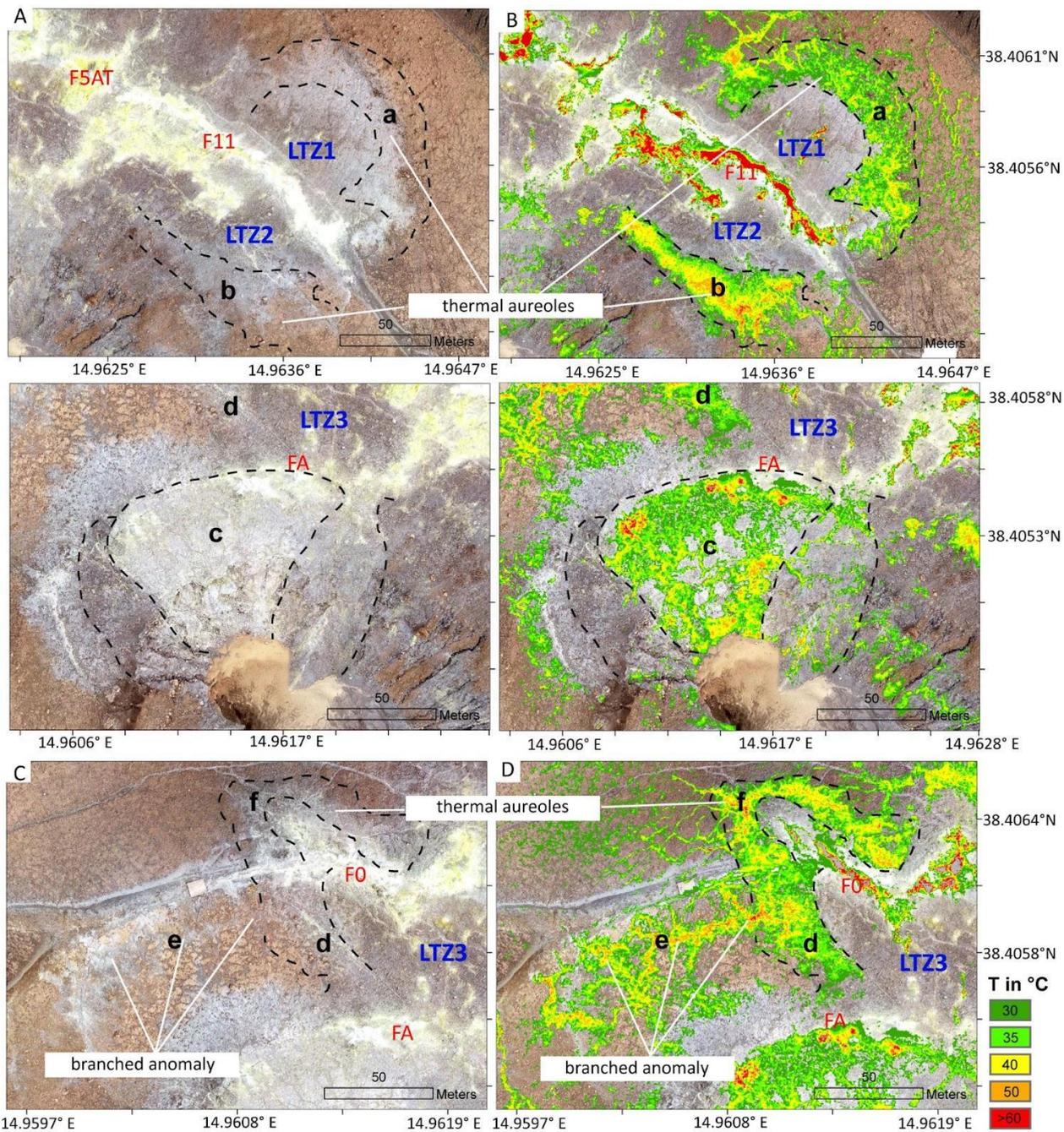
1996
1997 Figure C1: Detail views of distinct units a-f and LTZ1-3 in a true color representation as seen from our 2019 orthomosaic data
1998 and an overlay by the thermal data with T$\geq$ 30 °C. A/B) Shown are units 1 and b and respective LTZ1 and 2. Note the
1999 outward spatial offset of both thermal units with respect to the surface coloration. C/D) Unit c is characterized by a network
2000 of thermal anomalies embedded in the colder ~~surrounding~~surroundings. E/F) Thermal aureole d and f branched anomaly e.

Also here an outward shift of the thermal feature with respect to the surface coloration ~~os~~is observed, ~~that~~which could indicate gradual sealing processes with proximity to the main vents.

Appendix D: Spearman correlation test for non-normal distributed variables

The test for correlation between optical and thermal anomalies was performed using the ggpubr package (Kassambara, 2019) in the statistical software environment R. The method used was Spearman's rank correlation which is suggested to be used for non-normal distributed data. The correlation test is based on the vectorized classification raster data set (classp_fumclip) with 8,890,830 data points with the analyzed variables pixel class (0-32) and pixel temperature (20- 150°C). The results show a correlation factor of 0.3485299, which is considered a mean positive correlation, and a p-value of 2.2e-16 proves statistical significance.

Spearman's rank correlation rho
data: x and y
S = 7.6277e+19, p-value < 2.2e-16
alternative hypothesis: true rho is not equal to 0
sample estimates:
rho
0.3485299

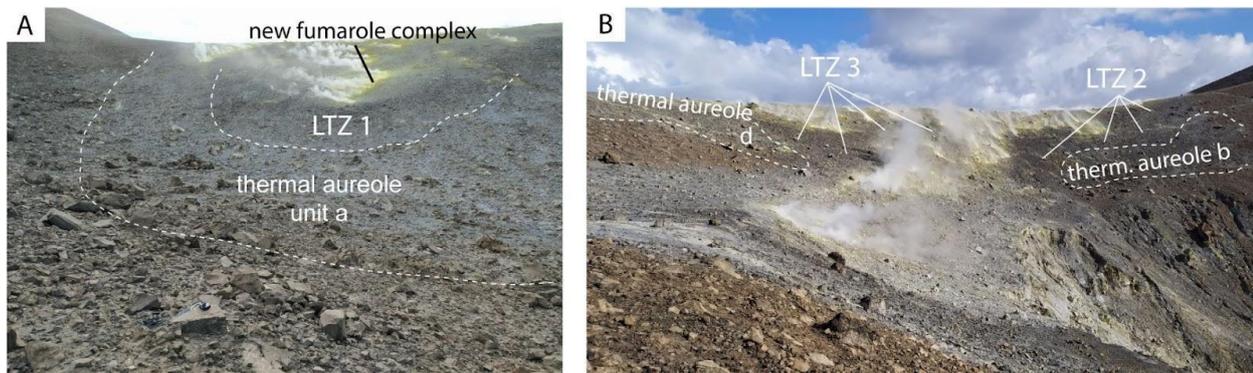**Appendix E: Thermal aureoles and LTZ indicated in field photographs**
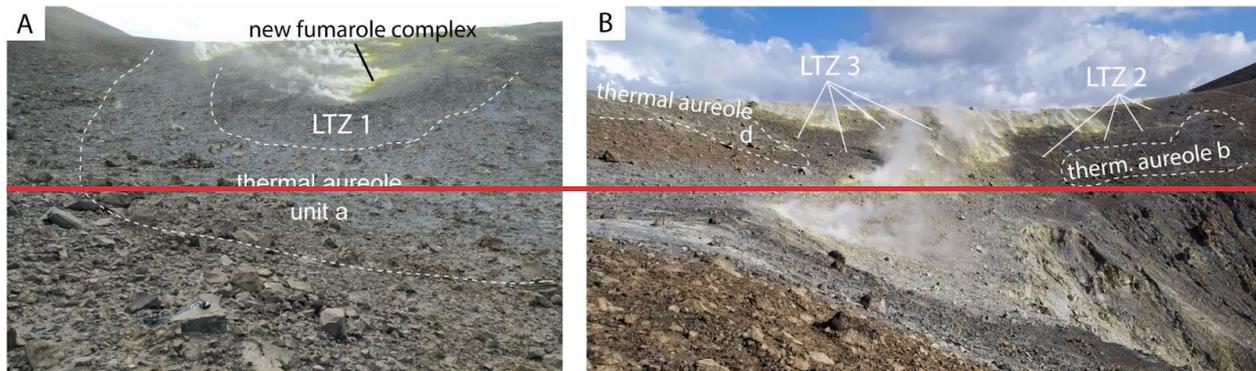
Figure E1: Thermal aureoles and low-temperature zones (LTZ) depicted on field photographs. A) Thermal aureole a and LTZ1. B) Thermal aureole b and d with LTZ2 and LTZ3.

Appendix F:

Table F1: XRD results of samples taken along transect A and B

Sample ID	A1	A2	A3	A4	A5	A6	B1	B2	B3
Sanidine	86.7	85.7	87.4	61.5	72.2	60.3	68.2	49.2	0
Cristobalite	13.3	14.3	12.6	18.2	0	0	0	0	0
Coesite	0	0	0	0	0.7	0	0	0	0
Sulfur	0	0	0	20.3	25.1	39.7	31.8	50.8	100
amorphous	50	0	0	0	0	50	50	0	0

Appendix G: XRF results of samples taken along transects A-C.

Table G1: XRF results of samples taken along transects A-C. Note that samples with S > 10 % were not analyzed by XRF.

S-ID	SiO$_2$ (%)	TiO$_2$ (%)	Al$_2$O$_3$ (%)	Fe$_2$O$_3$ (%)	MnO (%)	MgO (%)	CaO (%)	Na$_2$O (%)	K$_2$O (%)	P$_2$O$_5$ (%)	LOI (%)	S Eltra (%)
A1	76.0	0.2	10.7	1.6	0.1	0.1	1.1	1.8	4.8	0.1	3.8	0.1

A2	76.2	0.4	10.6	1.5	0.1	0	0.8	1.5	5.0	0.1	3.9	0.3
A3	77.0	0.3	10.2	1.4	0.1	0	0.7	1.6	4.8	0.1	4.3	0.2
A4	x	x	x	x	x	x	x	x	x	x	x	11.7
A5	67.3	2.2	0.4	0.3	11.9	0.1	1.2	3.1	5.0	0.1	2.0	6.0
A6	71.0	1.2	0.3	0.3	6.7	0.0	0.4	1.3	2.7	0.0	9.8	6.3
B1	73.0	1.2	0.3	0.3	7.0	0.0	0.5	1.3	3.0	0.0	4.3	9.0
B2	x	x	x	x	x	x	x	x	x	x	x	31.9
B3	x	x	x	x	x	x	x	x	x	x	x	60.5
C1	69.7	0.4	8.4	2.0	0	0.3	1.0	2.4	4.2	0.1	11.3	0.1
C2	81.3	0.3	6.1	1.1	0	0.1	0.4	1.1	2.5	0	6.1	0.5
C3	77.4	0.4	7.6	1.8	0	0.2	0.9	2.0	4.0	0.1	5.1	0.4
C4	x	x	x	x	x	x	x	x	x	x	x	40.3
C5	x	x	x	x	x	x	x	x	x	x	x	26.2
C6	x	x	x	x	x	x	x	x	x	x	x	12.5
C7	x	x	x	x	x	x	x	x	x	x	x	17.5
C8	63.8	0.4	12.0	3.2	0.1	0.4	1.7	5.0	8.0	0.1	3.2	1.2
C9	68.9	0.4	11.4	1.5	0	0.4	1.3	3.0	4.7	0.1	8.1	0.2

10 Data availabiltyavailability

Data will be made available on request for now and will be published on Zenodo in case of acceptance for revision during the revision of this manuscript.

11 Author contributions

D.M conceptualized the study, collected data, performed the remote sensing and gas analysis, and led the manuscript writing. T.R.W. provided funding, supported the conceptualization, and supervised the writing. V.T. supported the conceptualization,

performed XRD analysis, and supervised the writing. J.S. performed XRF analysis and supported the writing. A.K. performed XRD analysis and supported the writing. E.D.P. collected data and samples, supported all field works and the writing of this manuscript. A.F.P. supported fieldwork and on the ground logistics, acquired data, and supported the writing. M.Z. supported the gas measurement campaign and supported the writing. B.D.J. supported the fieldwork and writing of this manuscript.

12 Competing interests

The authors declare that they have no conflict of interest.

13 Acknowledgements

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