EUROVOLC

European Network of Observatories and Research Infrastructure for Volcanology

Deliverable Report

D10.4 : Best practice in petrological monitoring of eruptions

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Contents

Summary

This report summarizes the activities developed in the framework of EUROVOLC subtask 10.2.2. The aim of this subtask is to produce three reviews that consider different petrological aspects which include the state of art of petrology methods and suggestions about which are the hard-core practices for petrological monitoring. The reviews are entitled as follow:

1. Review of P, T, X information from petrology methods. (Lead INGV)
2. Review of petrological practices European institutions have adopted during recent eruptions, to identify best practice and formulate guidelines. (Lead INGV)
3. Assessment of ^{226}Ra-^{210}Pb-^{210}Po radioactive disequilibria and volatile accumulation before recent eruptions, and integration with deformation. (Lead UCA)

1) Review of P, T, X information from petrology methods and discussion of results and implications for prioritisation of monitoring strategies definition of PTX

Petrological monitoring methods focus on the study of the solid erupted products of volcanic activity, with a view to understanding the magmatic history of those products, in terms of transport pathways, storage zones and timescales of magmatic events. Petrological monitoring has at least two modes of action. The syn-eruptive study is conducted during the volcanic crisis and has immediate benefit for the monitoring framework. Syn-eruptive investigation purpose is to build a more comprehensive petrological picture as the volcanic crisis unfolds to integrate and synthetize with information acquired by other monitoring techniques. The syn-eruptive study can be completed by extended petrological investigations that generally takes additional time and seeks to place constraints on specific processes and to refine in great detail our understanding of particular aspects of the eruption behaviour. We concentrate our attention mainly on studies that improve the understanding of the P-T-X conditions of magma storage. For the purposes of this review, "P" is for pressure, "T" is for temperature, "X" refers to the composition of the magma and to the volatile content.

Table 1 summarises major contributions of key references (at selected volcanoes and eruptions) to our understanding of P-T-X information. It represents a compilation of papers dealing with both syn-eruptive and extended petrological monitoring. Among the key references, even though only a few were published while the eruptions were still ongoing, most of the data were produced during syn-eruptive phases being pieces of proper petrological monitoring. A consistent number of them were instead published years after the eruptive crisis was finished, but were still based on sampling, analyses and unpublished reports produced during the eruption. A latter group of publications, based on "ad hoc" laboratory experiments and on samples collected during the eruptions, are here included because they provide richer context of the eruption dynamic and salient lessons valuable for future eruptive crises. In some cases, we also consider some examples of the investigation of timescales (t) of magmatic processes that can ultimately be linked to geophysical monitoring data (see EUROVOLC task 10.2.1).

Petrological monitoring has often focussed on basaltic systems because they commonly have long-lived effusive eruptions (e.g. 1983-2018 eruption of Kilauea, Hawaii, or 1991-93 Etna), or a high frequency of eruptions (e.g. Etna, Stromboli, Italy). Nevertheless, in addition to cases representing different kinds of basaltic eruptions, we also added references related to Soufrière Hills volcano (Montserrat, West Indies) and Mt. St. Helens (USA) since both represent an exceptional opportunity to monitor, with petrological methods, long-lived dome-forming eruptions of an andesite/dacite magma.

Table 1

Volcano	Publication	Techniques Used	Results
Etna	Trigila, R., Spera, F.J. & Aurisicchio, C. The 1983 Mount Etna eruption: thermochemical and dynamical inferences. Contr. Mineral. and Petrol. 104, 594–608 (1990). https://doi.org/10.1007/BF00306667	Thermochemical calculations and laboratory phase equilibration experiments on lavas of 1983 Mt. Etna flank eruption to investigate possible systematic variations in inferred melt-phenocryst equilibration conditions as a function of time. Total pressures, temperatures and dissolved H2O concentrations were calculated using the isoactivity method of Carmichael et al. (1977)	Total pressures (Pt), temperatures and H2O contents based on representative olivine-clinopyroxene pairs are 140 MPa, 1105 °C, 2.4 wt% H2O; 255 MPA, 1112 °C, 1.0 wt% H2O and 85 MPa, 1096 °C, 1.8 wt% H2O respectively for samples erupted during the early, middle and late phases of the eruption. Corresponding equilibration depths are in the range 3 to 10 kilometres. The pre-eruptive (i.e., in situ) temperature-pressure gradient calculated from olivine-clinopyroxene equilibria is 10.6 K/kbar.

	Metrich N, Allard P, Spilliaert N, Andronico D & Burton M. 2001 flank eruption of the alkali- and volatile-rich primitive basalt responsible for Mount Etna's evolution in the last three decades. Earth Planet Sci Lett 228(1-2), 1-17 (2004)	Major elements and volatiles content in melt inclusions hosted within three populations of olivine crystals erupted at Lower vents during the 2001 eruption. The compositions of olivine crystals and of their melt inclusions, including S, Cl and F contents, were measured with an electron microprobe. The dissolved amounts of water and carbon were determined using an infrared spectrometer (FTIR).	The primitive inclusions in skeletal olivines (population I) were trapped under total fluid pressures ranging from ~500 to 250 MPa, indicating polybaric melt entrapment during magma ascent; the primitive basalt rose from ~12 to 6.5 km b.s.l. Another evolution path is defined by melt inclusions hosted in heterogeneous euhedral olivine (population II) that disclose trapping pressure of ~200 MPa, suggesting a preeruptive storage of the slightly more evolved, crystallised magma at ~5 km b.s.l. A persistent level of magma ponding and crystallisation at ~6 km depth b.s.l. is also supported by the comparable entrapment pressure (~250 MPa) derived for the 2001 samples and the pre-1970s melt inclusions trapped in Fo77.5 olivine xenocrysts.
	Corsaro, R.A., Miraglia, L. & Pompilio, M. Petrologic evidence of a complex plumbing system feeding the July–August 2001 eruption of Mt. Etna, Sicily, Italy. Bull Volcanol 69, 401 (2007). https://doi.org/10.1007/s00445-006-0083-4	Combination of petrographical, textural, mineral composition, major and trace elemental bulk rock analyses, and thermodynamic modelling (MELTS) to constrain different intratelluric conditions for magma erupted from the Upper and Lower vents during 2001 eruption	The isobaric cooling of magma from liquidus to the eruptive temperature was performed at pressures in the range of 200–0.1 MPa, with different initial water contents (from dry up to 3%), and with oxygen fugacity fixed on the QFM buffer. The initial magma composition corresponds to the most primitive erupted magma. Results reveal that the cooling of a water-rich liquid at P greater than few tenths of MPa, would originate magma similar to that produced by Lower vents, with low crystal content mainly formed by mafic phases. Conversely, the cooling of a nearly totally degassed magma, as that stationing at very shallow depth, would produce a crystal-rich magma in which plagioclase is the dominant phase, similar to that produced by Upper vents.
	Maren Kahl, Sumit Chakraborty, Massimo Pompilio, Fidel Costa, Constraints on the Nature and Evolution of the Magma Plumbing System of Mt. Etna Volcano (1991–2008) from a Combined Thermodynamic and Kinetic Modelling of the Compositional Record of Minerals, Journal of Petrology, Volume 56, Issue 10, October 2015, Pages 2025–2068, https://doi.org/10.1093/petrology/egv063	Combination of diffusion chronology of zoned olivine crystals and thermodynamic modelling (MELTS) to constrain the nature and evolution of the plumbing system of Mt. Etna and the processes governing its internal dynamics. Assessment of key intensive variables (pressure, temperature, water content, oxygen fugacity and bulk composition of the melt) associated with the different magmatic environments that are compatible with the population of olivine compositions erupted during the period 1991-2008.	The most primitive olivine population M0 (Fo79–83) formed at high melt water contents (3.5-5.2wt %), at fO2 conditions buffered at quartz–fayalite–magnetite (QFM) or Ni–NiO (NNO), at temperatures ≥1110°C and at pressures ranging between 1.5 and 3.0 kbar (or higher). M1 olivines allow many combinations but on the whole require lower water contents (0.1–1.4wt %); the high-An (80–83) plagioclase compositions can be produced only with M1 olivines at QFM, low water contents (0.5 and 1.4wt %), pressures between 0.75 and 0.25 kbar and temperatures between 1100 and 1160°C. The more evolved olivine compositions corresponding to M2 and M3 can be formed only by fractional crystallization, at lower temperatures (1080°C) low water contents, and only under QFM conditions. M2 olivines (Fo70.5–72) form at water contents ranging between 0.2 and 1.1wt % M3 olivines (Fo65–69) also form at QFM only, at even lower melt water contents (0.2–0.4wt %). The low water contents required to produce the M2 and M3 type olivines suggest that these formed at low pressures.
	Taddeucci J, Pompilio M & Scarlato P. Conduit processes during the July–August 2001 explosive activity of Mt. Etna (Italy): inferences from glass chemistry and crystal size distribution of ash particles. J Volcanol Geotherm Res 137 (1–3):33–54 (2004)	Application of the experimentally calibrated geothermometer of Pompilio et al (1998) based on the MgO content of the residual glasses	The eruptive temperatures of tachylite glasses are always lower (~30-40 °C) than those of sideromelane glasses. The average temperatures for sideromelane and tachylite are respectively 1077 °C and 1044 °C during phreatomagmatic phase, 1082 °C and 1042 °C during strombolian fire fountain phase, and 1073 °C and 1052 °C during pulsing ash explosion phase
Stromboli	Métrich et al., 2010. Conditions of Mama storage, Degassing and Ascent at Stromboli: New Insights into the Volcano Plumbing	Major elements and volatiles (CO_2, H_2O, S and Cl) compositions in olivine (Fo_{90-85})-hosted melt inclusions and embayments.	The highest melt saturation pressure (P_{H2O}+P_{CO2}) retrieved from Ca-rich melt inclusions is 280 MPa, equivalent to a maximum 11km lithostatic depth, using an average crustal density of 2700 kg/m^3.

	System with Inferences on the Eruptive Dynamics. *Journal of Petrology*, 51: 603-626.	Major element and S, Cl, P concentrations of melt inclusions were measured by EMPA; CO_2 concentrations were determined with nuclear microprobe, while Micro-Raman spectroscopic analyses were performed for quantifying the total amount of dissolved water (H2O+OH).	The saturation pressures range from 280 to 190MPa (7-10 km); values ≤190MPa are determined in unsealed glass embayments for which the pressure regularly decreases to ~40 MPa.T= 1120°C
	Pichavant et al., 2009. "Experimental Constraints on the Deep Magma Feeding System at Stromboli Volcano, Italy"- Journal of Petrology, 50:601-624.	High-pressure, fluid-present experiments, (2) high-pressure, olivine-added experiments and (3) 0·1 MPa experiments have been performed. In all these experiments, the starting material is the golden pumice sample PST-9.	Most inclusions were trapped at pressures of 150–250 MPa. This constrains the depth of olivine crystallization in the reservoir source of golden pumice magmas (5.7–9.4 km). LP magmas at their storage level have an average temperature of 1150°C.
	Di Carlo et al., 2006. "Experimental Crystallization of a High-K Arc Basalt: the Golden Pumice, Stromboli Volcano (Italy).	Experiments on glass powder of natural samples performed with an internally heated pressure vessel at four experimental variables: pressure, temperature, $melt_{H2O}$ content and fO_2.	The storage region of the golden pumice melt is in the depth range 3.8–10.2 km (7.5 km for 200 MPa) within the metamorphic arc crust. T= 1140–1160°C.
	Vagelli et al., (2003). " Persistent polybaric rests of calc-alkaline magmas at Stromboli volcano, Italy: pressure data from fluid inclusions in restitic quartzite nodules". Bulletin of Volcanology 65:385-404	Microthermometric, microprobe and Raman spectroscopy investigations on CO_2 inclusions in quartzite nodules hosted by calc-alkaline lavas of both the Strombolicchio (200 ka) and Paleostromboli II (60 ka) periods.	290 MPa (11 km) for the depth storage region and 100 MPa (3.5 km) for the shallow reservoir.
Piton de la Fournaise	Di Muro, A., Métrich, N., Vergani, D., Rosi, M., Armienti, P., Fougeroux, T., Deloule, E., Arienzo, I., Civetta, L., 2014. The shallow plumbing system of Piton de la Fournaise Volcano (La Réunion Island, Indian Ocean) revealed by the major 2007 caldera-forming eruption. J. Petrol.55, 1287–1315. https://doi .org /10 .1093 /petrology /egu025.	Extensive investigation of products erupted during the April 2007 caldera-forming eruption. Measures of volatile (H2O and CO2) content within olivine-hosted melt inclusion allowed the calculation of the total fluid pressures with VOLATILECALC (Newman & Lowenstern, 2002). The olivine-melt equilibrium temperatures are calculated using the Helz & Thornber (1987) geothermometer.	Melt inclusions in oceanite olivines indicate low-pressure magma storage and crystallization from 48 to 13MPa (PCO2 +PH2O); most values vary between 34 and 18MPa. It corresponds to an interval of lithostatic depths from 1800 to 500m (on average 1020m; 27MPa) below the surface. Average temperature values are 1174°C, 1200°C and 1188°C for samples of 30 March, 2-3 April and 25 April respectively.
	Albert H, Costa F, Di Muro A, Herrin J, Métrich N, Deloule E (2019) Magma interactions, crystal mush formation, timescales, and unrest during caldera collapse and lateral eruption at ocean island basaltic volcanoes (Piton de la Fournaise, La Réunion). Earth Planet Sci Lett 515:187–199. https://doi.org/10.1016/j.epsl.2019.02.035	Crystal and melt inclusion compositions of the April 2007 caldera-forming eruption. Volatile concentrations (H2O and CO2) coupled with experimentally calibrated solubility models allows the determination of the volatile saturation pressure, which can be translated into minimum depth of magma storage. Temperatures have been calculated with the Fo values and the melt inclusions composition by using the olivine-melt equilibrium geothermometer of Helz and Thornber (1987), as described by Di Muro et al. (2014).	The H2O and CO2 contents of the melt inclusions range from 0.6–1.1 wt% and 53 to 125 ppm, respectively, for the pre-caldera tephra, and from 0.32–0.82 wt% and 56 to 205 ppm for the post-caldera lava (Di Muro et al., 2014). These concentrations correspond to low saturation pressures (<0.5–0.4 kbar), that corresponds to a lithostatic depth range of 1280–1100 m below the volcano summit (ca. 1.5 km above sea level). Temperatures calculated for post-entrapment crystallization show a larger range (1145 to 1232 °C) in pre-caldera samples, compared to post-caldera melt inclusions (1178 to 1199 °C).
St. Helens	Melson, W.G., and Hopson, C.A., 1981, Preeruption temperatures and oxygen fugacities in the 1980 eruptive sequence, in Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S.	Pre-eruption temperatures and oxygen fugacities are inferred using the experimental results of Lindsley (1976, 1977) based on electron microprobe analyses of coexisting ilmenite and magnetite	Experimental results give an average temperature of 990°C and an average oxygen fugacity of -9.7 bars (expressed as log to the base 10) for the 1980 eruptive sequence. Analyses of the A.D. 1800 air-fall pumice (pumice of layer T) give similar values, whereas those of A.D.

	Geological Survey Professional Paper 1250, p. 641–648.		1500 pumice (pumice of set W) give lower values (average of 840°C at log fo2 = -12.5 bars).
	Blundy, J., and Cashman, K., 2001, Ascent-driven crystallisation of dacite magmas at Mount St. Helens, 1980–86: Contributions to Mineralogy and Petrology, v. 140, no. 6, p. 631–650, doi:10.1007/s004100000219.	Natural silicic glasses are projected into the synthetic system Qz±Ab±Or±H2O in order to relate variations in volcanic glass chemistry to changing pressure (P) and temperature (T) conditions in the sub-volcanic magma system. In samples containing feldspar and a silica phase (quartz or tridymite), quantitative P±T estimates of the conditions of last equilibrium between crystals and melt can be made.	The compositions of the least evolved (SiO2-poor) inclusions in amphibole phenocrysts record entrapment of silicic liquids with ≤ 5.4 wt% water, corresponding to a water saturation pressure of ~ 200 MPa at 900°C. The compositions of the more evolved (higher SiO2) plagioclase-hosted inclusion and groundmass glasses are consistent with extensive ascent-driven fractional crystallization of plagioclase, oxide and orthopyroxene phenocrysts and microlites to low pressure. At pressure of ~ 300 MPa magma begins to crystallize amphibole and orthopyroxene. At ~ 200 MPa water reaches saturation pressure and exolves, and magma begins to crystallize also plagioclase (An60) and Fe-Ti oxides. The major Plinian episode of the 18 May 1980 eruption tapped magma at a pressure of ~150 MPa (depth of 5-6 km). Subsequent eruptions that produced both pumice and dome samples were fed by a magma equilibrated at pressures ≤ 150 MPa
	Pallister, J.S., Thornber, C.R., Cashman, K.V., Clynne, M.A., Lowers, H.A., Mandeville, C.W., Brownfield, I.K., and Meeker, G.P., 2008, Petrology of the 2004–2006 Mount St. Helens lava dome—Implications for magmatic plumbing and eruption triggering, in Sherrod, D.R., et al., eds., A volcano rekindled: The renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750, p. 647–703	Crystallization pressures are estimated with the projection of glass compositions of 2004-2006 Mount St. Helens samples onto ternary diagram quartz-albite-orthoclase modified by Blundy and Cashman (2001). The abundance of H2O in matrix and inclusion glasses is used to further constrain depths. Temperature of the 2004-2006 lava dome have been estimated by Fe-Ti oxide thermobarometry	Crystallization pressures for the most evolved matrix glasses occurred between 50 MPa and 0.1 MPa. The presence of tridymite in some samples restricts the pressure for matrix crystallization and solidification to the range 11–25 MPa (depth 0.5–1.0 km) at temperature 885–915°C. Matrix and inclusion glasses show a decline in water content from approximately 2.3 % H2O at 73.5% SiO2, to less than 0.1% at 77% SiO2. The upper end of this H2O range is indicative of quenching at a pressure of about 30 MPa (depth of 1.4 km) followed by decompression-driven crystallization and quenching of residual melt, which continued to pressures of less than 10 MPa (depth about 0.5 km). Oxide thermobarometry determinations for the earliest erupted samples cluster at temperatures of approximately 850°C and at an oxygen fugacity one log unit above the nickel-nickel oxide (NNO) buffer curve. In contrast, samples from relatively glass-poor samples erupted in late 2004 and early 2005 have zoned oxides with apparent temperatures higher than 950ºC.
Holuhraun-Bardabunga	Geiger, H., T. Mattsson, F. M. Deegan, V. R. Troll, S. Burchardt, O. Gudmundsson, A. Tryggvason, M. Krumbholz, and C. Harris (2016), Magma plumbing for the 2014–2015 Holuhraun eruption, Iceland, Geochem. Geophys. Geosyst., 17, 2953–2968, doi:10.1002/2016GC006317.	Mineral-melt thermobarometry	Clinopyroxene-melt thermobarometry applied to mineral-whole rock couples (Putirka 2008) resulted in an average crystallization pressure of 471 MPa, corresponding to a crystallization depth of ~17 km, and to a calculated average temperature of 1193°C. Plagioclase-melt thermobarometry applied to mineral-groundmass couples resulted in an average crystallization pressure of ~141 MPa, which translates to ~5.2 km depth. Thermobarometry calculations indicate a polybaric magma plumbing system for the Holuhraun eruption, wherein clinopyroxene and plagioclase crystallized at average depths of ~17 km and ~5 km, respectively
	Caracciolo A, Bali E, Guðfinnsson GH, Kahl M, Halldórsson SA, Hartley ME, Gunnarsson H, 2019. Temporal evolution of magma and crystal mush storage conditions in the Bárðarbunga-Veiðivötn volcanic system, Iceland, Lithos, Volumes 352–353,	Measures of the major and minor elemental composition of glass, mineral and melt inclusion from five erupted units that span a full glacial cycle, from a <100 ka subglacial eruption to a historical eruption in 1477 AD. All samples contain macrocrysts (>500 mm), which rims are in chemical equilibrium with their	Clinopyroxene-melt and melt-based (olivine-plagioclase-augite-melt) geobarometers reveal temporally invariant crystallization conditions of 1.9-2.2 ± 0.7 (1 sigma) kbar pressure, corresponding to depths around 6.8-7.8 ± 2.5 km. All the samples also contain melt inclusions trapped at mid-crustal pressures of ~2.6 kbar (9.6 km). In addition, melt inclusions hosted in more primitive olivines and plagioclases from subglacial and early Holocene eruptions preserve evidence of crystallization in a

	2020, 105234, ISSN 0024-4937,https://doi.org/10.1016/j.lithos.2019.105234.	respective carrier melts, while macrocrysts cores are too primitive to have crystallized from these melts.	lower-crustal storage level(s) located at 17.5 km (4.9 kbar).
El Hierro - Canary Islands	Martí, J., A. Castro, C. Rodríguez, F. Costa, S. Carrasquilla, R. Pedreira and X. Bolos (2013b). Correlation of Magma Evolution and Geophysical Monitoring during the 2011-2012 El Hierro (Canary Islands) Submarine Eruption, J. Pet., 54 (7), 1349-1373; doi:10.1093/petrology/egt014.	The application of petrography, mineral chemistry, geochemistry, and experimental petrology, including mineral-melt thermodynamic and diffusion modelling on quenched basanitic magma samples from the 2011-2012 submarine eruption of El Hierro has permitted the identification of major physico-chemical variations prior to and during magma eruption.	Based on petrological and geophysical data two main eruptive episodes were distinguished. Magma erupted from October until late November 2011 was an evolved basanite (~5wt% MgO), changing to more primitive compositions (~8-9 wt% MgO) with time, suggesting the extraction from a compositionally zoned magma system. Experimental data and mineral-melt thermodynamic modelling indicate that the erupted magma equilibrated at a pressure of about 400MPa, which corresponds to a depth of 12-15km, consistent with the location of the crust-mantle discontinuity beneath El Hierro. Preliminary modelling of the olivine chemical zoning of crystals erupted in this first episode suggests that the time scale for basanite fractionation and magma replenishment in this 12-15km reservoir was of the order of a few months. An abrupt change in magma composition and crystal content was observed at the end of November 2011, when a more primitive and less viscous magma was erupted. This correlates with an intrusion of fresh, more primitive magma into the shallow magmatic system that raised the temperature of the resident magma. Experiments reveal that subtle changes in temperature of about 50°C (i.e. 1100-1150°C) were enough to produce large changes in the crystal content (10-60 wt %)
	Longpré, M.A., A. Klügel, A. Diehl and J. Stix (2014). Mixing in mantle magma reservoirs prior to and during the 2011-2012 eruption at El Hierro, Canary Islands, Geology; doi:10.1130/G35165.1	Clinopyroxene-melt (Putirka et al., 2003) and fluid inclusion (Hansteen and Klügel, 2008) geobarometry to constrain the crystallization depths of magma feeding the 2011-2012 submarine eruption at El Hierro.	At least two distinct magmas initially supplied from reservoirs in the mantle underwent hybridization at 15–25 km depth, and the process of magma mixing began during the period of pre-eruptive seismicity and continued for weeks after the eruption onset. Based on analyses of 73 clinopyroxene rims in textural and chemical equilibrium with host basanite glass, calculation suggest final phenocryst growth at 500–710 MPa, that correspond to 17– 24 km depth beneath the volcano (within the upper mantle). In comparison, homogenization to liquid CO_2 for 260 olivine- and clinopyroxene-hosted fluid inclusions correspond to entrapment and/or re-equilibration pressures of 280–580 MPa at 1150 °C, equivalent to 10–20 km depth beneath El Hierro
	Meletlidis, S., Di Roberto, A., Cerdeña, I. D., Pompilio, M., García-Cañada, L., Bertagnini, A., et al. (2015). New insight into the 2011–2012 unrestand eruption of El Hierro Island (Canary Islands) based on integrated geophysical, geodetical and petrological data. Annals of Geophysics,58(5), S0546. https://doi.org/10.4401/ag-6754	Detailed mineralogical and geochemical analysis, and thermodynamical modeling of magma differentiation, of products systematically sampled during the 2011-2012 El Hierro submarine eruption. These data were combined with the temporal analysis of seismic events, ground deformation patterns and gravity data, to give a multi- disciplinary view of the dynamics of magma ascent, improving previous interpretations formulated during or shortly after the end of the eruption.	The eruption was fed by a single batch of mantle-derived magma, progressively migrating and tapped three different magmatic environments. Bulk rocks compositions varied significantly during the eruption with a progressive and continuous shift towards more mafic term due to crystals fractionation and crystals cumulus of mafic phases, which increased from 5 wt% in the first day of the eruption up to 20 wt% during late phase. Thermodynamic modelling cannot discriminate if this process occurs in the mantle reservoir at P = 700 MPa, temperature between 1220 and 1190°C and under reduced fO_2 (QFM) or at crustal levels at P = 350 MPa, temperature between 1180 and 1160°C, under more oxidized conditions (fO_2 = NNO+1). However, the observed compositional variations imply the existence of a zoned magma body that is progressively withdrawn during the eruption.
Montserrat	Barclay, J., et al., 1998. "Experimental phase equilibria constraints on pre-eruptive storage conditions of the Soufriere Hills magma."	High Pressure experiments on samples representative of bulk rock compositions to replicate the conditions of magma storage. The water contents of quartz and plagioclase-hosted melt	Amphibole is unstable in the magma at P< 115 MPa (depth ≈4km), suggesting magma storage at higher pressures. Melt inclusion water contents of 4.8 wt% would equate to a saturation pressure of 130 MPa (depth ≈5km),.

	Geophysical Research Letters, 25(18), 3437-3440.	inclusions were determined by fourier transform infrared spectroscopy (FTIR). Experiments on powders and glasses at pressures and temperatures of magma storage were performed to understand how phase stability constrained magma storage conditions. Samples stored in $Ag_{70}Pd_{30}$ capsules	At the relevant pressures of magma storage quartz is only stable at T < 840˚C. The presence of resorbed quartz shows initial magma temperatures were low, but increased before eruption, likely in response to mafic magma recharge. Magma is heated to less than 880˚C, taking into account the lack of thermal breakdown of amphibole.
	Murphy, M. D., et al., 1998. "The role of magma mixing in triggering the current eruption of Soufriére Hills volcano, Montserrat, West Indies." *Geophysical Research Letters,* 25(18), 3433-3436.	Use a geothermometry programme called QUILF to estimate temperatures. Requires analysis of orthopyroxene composition by electron microprobe.	Use composition of homogeneous orthopyroxene cores from the mafic inclusions to constrain the temperature of the mafic magma recharge to 1020-1050˚C.
	Devine, J. D., et al., 1998a. "Petrologic evidence for pre-eruptive pressure-temperature conditions, and recent reheating, of andesitic magma erupting at the Soufriére Hills Volcano, Montserrat, W.I." *Geophysical Research Letters,* 25(19), 3669-3672.	Amphibole composition analysed by electron microprobe.	Al-in-amphibole geobarometer gives magma storage pressure of ~ 130 MPa.
	Devine, J. D., et al., 2003. "Magma storage region processes inferred from geochemistry of Fe-Ti oxides in andesitic magma, Soufriére Hills volcano, Montserrat, W.I." *Journal of Petrology,* 44(8), 1375-1400.	Electron probe micro-analysis (EPMA) of Fe-Ti oxide pairs (titanomagnetite and ilmenite). Samples are a time series from 1995 to 2002. Both spot analyses and transects were undertaken.	Temperature estimates for this period refined to being consistently about 825˚C before mafic magma recharge, arguing against global heating of the reservoir.
	Devine, J. D. & Rutherford, M. J., 2014. "Magma storage region processes of the Soufriére Hills volcano, Montserrat." In Wadge, G., Robertson, R. E. A. & Voight, B. (eds). *The Eruption of Soufriére Hills Volcano, Montserrat from 2000 to 2010.* Geological Society, London, Memoirs, 39**,** 361–381**.**	EPMA analysis of Fe-Ti oxide pairs, for samples erupted on the 11th February, 2010.	Pre-recharge temperature for the 2010 lavas is 835˚C, which is argued to reflect a 10˚C global heating of the magma reservoir. This interpretation is supported by the complete absence of quartz, which becomes unstable at higher temperatures.
	Edmonds, M., et al., 2016. "Extensive, water-rich magma reservoir beneath southern Montserrat." *Lithos,* 252-253, 216-233.	Analysis of the water contents of melt inclusions and the OH content of orthopyroxene. Both were measured by secondary ion mass spectrometry (SIMS)- the former at the ion microprobe facility in Edinburgh, UK, the latter at the Carnegie Institute in Washington DC, USA.	While melt inclusion water contents are 0-6.3 wt%, the OH content of orthopyroxene gives equilibrium water contents of melt mostly in the 6-9 wt% range. Analysis of a small number of orthopyroxene hosted melt inclusions give consistent results with the host crystal. The different techniques are recording different parts of the system- melt inclusions are trapped at depths averaging 5 km, while orthopyroxene record depths of 10-16 km.

2) Review of petrological monitoring procedures to identify best practices

Within the framework of the EUROVOLC project, a questionnaire was developed to review the petrological monitoring procedures performed during eruptions by academia, volcano observatories, research laboratories and other monitoring institutions (hereafter referred as institutions in general). The questionnaire aimed at surveying the common procedures adopted by these institutions, to identify the most common techniques and to rate their suitability in terms of costs versus benefit (e.g., time and resource versus rate of relevance of the obtained result). The aim was to design best practices that could be adopted from European Volcano Observatories (and other worldwide institutions) to efficiently conduct petrological monitoring during ongoing eruptions. Also, one of the questionnaire's purposes was to highlight the problems that affect petrological monitoring, to constrain whether they depend on institution capabilities (e.g., shortage of qualified staff, lack of facilities and/or of financial resources) or relate to gaps in knowledge (e.g., lack of geological background information, or lack of guidelines), and to suggest solutions that allow a profitable petrological monitoring infrastructure.

The questionnaire (Available online at: https://forms.gle/8i4Z8bFAjvLrLD8d8) was designed taking into consideration these needs. It is composed of the following nine sections: 1) Introduction and general information, 2) Staff, 3) Lava sampling strategy, 4) Pyroclasts sampling strategy, 5) Sample preparations, 6) Laboratory analyses, 7) Data results and collaborations with other monitoring scientists, 8) Data dissemination, and 9) Conclusion. The questionnaire includes "open-ended" questions that give the opportunity of extended answers with brief argumentation, and "closed-ended" questions that ask responders to i) respond in a yes/no format, ii) choose among any of given multiple choice answers, iii) rate a particular issue on a scale that ranges between poor to good.

The questionnaire was sent by email to the seventy-five scientists in charge at the volcano observatories listed in the World Organization of Volcanic Observatories (WOVO) webpage, and to other institutions (among academia and research institutes) outside the WOVO, for a total of about one hundred emails sent. It was also disseminated to the scientific community (to the attention of group leaders in petrological research teams in academia, volcano observatories and research institutions in general) through the Volcano ListServ. Eighteen institutions participated in the survey, sixteen of which are listed on the WOVO webpage (~ 21%) and two are from outside.

Results of the survey

Section 1 – Introduction and general information

In the first section of the survey, general information about the institution has been collected, such as name and type, what kinds of petrological research are conducted, and what volcanoes are monitored. Among the eighteen institutions that participated in the survey (Table 2; Figure 2.1a), there are academia (40%), research institutes (40%) and government departments (20%), and almost all of them deal with both syn-eruptive and extended (post-eruptive) petrological research (Figure 2.1b). Seven contributions are from America (39%), three from Oceania (16%), and six from Europe (33%). Depending on the volcano monitored by the responding institutions, a variety of activity is evaluated, from lava effusion to dome extrusion, and from weak to violent explosive activity. Thereby, the responding institutions offer points of view about volcanoes with different eruptive styles, magma compositions and background activity (e.g. persistent weak unrest; quiescence with open conduit; quiescence with close conduit, etc.), promoting some techniques/analyses compared to others.

Figure 2.1 - Pie charts illustrating the type of the responding institution (a) and the type of petrological research conducted (b). Both questions allowed multiple-choice answers, and the labels indicate the number of preferences and the percentage. The n value indicates the number of institutions that answered the question.

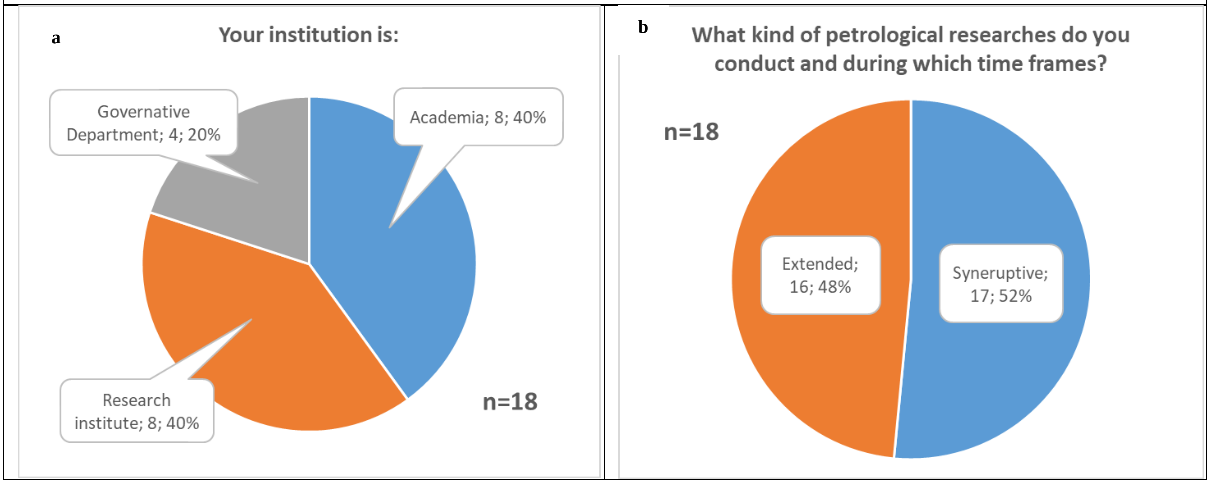


Table 2 - The eighteen responding institutions are listed below. Seven contributions are from America, three from Oceania, and six from Europe, plus an anonymous institution A-Academia, RI-Research Institute, GD-Governative Department

Nation	Type	Institution name	Acronym	Monitored volcanoes
Ecuador (ECU)	A	Instituto Geofísico - Escuela Politécnica Nacional	EPN	Stratovolcanoes and shield volcanoes of Ecuadorian continental arc and Galápagos. For example, eruptions of Tungurahua (1999-2016) and Cotopaxi (2015)
Colombia (COL)	RI	Servicio Geológico Colombiano - Observatorio Vulcanológico y Sismológico de Manizales	OVSM	Volcanoes of the North segment of Colombia, with a particular focus on monitoring the Nevado del Ruiz volcano from 1985 to the present.
Mexico (MEX)	A	Universidad de Colima	Uni Colima	Colima volcano. Recent eruptions are 2005 and 2015
Costa Rica (CRI)	A, RI	Observatory of Volcanology and Seismology of Costa Rica - National University	OVSICO RI	Costa Rican volcanoes. Notable eruptive crises are Turrialba (2012-2019), Poás (2017 and 2019) and phreatic phases (2014-present), Rincón de la Vieja (2016-present)
USA	A	New Mexico Institute of Mining and Technology	NMIMT	Monitoring of Erebus volcano from the early 1970 to Dec 2016, which contains a permanent lava lake and was continuously active.
USA	RI	USGS - Hawaiian Volcano Observatory	USGS - HVO	All Hawaiian Volcanoes. Notable eruptions are Kilauea 2018, Puu Oo 1983-2018, Mauna Loa 1084
USA	GD	USGS - Alaska Volcano Observatory *[two contributes]*	USGS - AVO	Volcanoes of Alaskan, Aleutian Arc, and in the Commonwealth of the Northern Mariana Islands. Recent eruptions are Augustine 2006, Redoubt 2009, Bogoslof

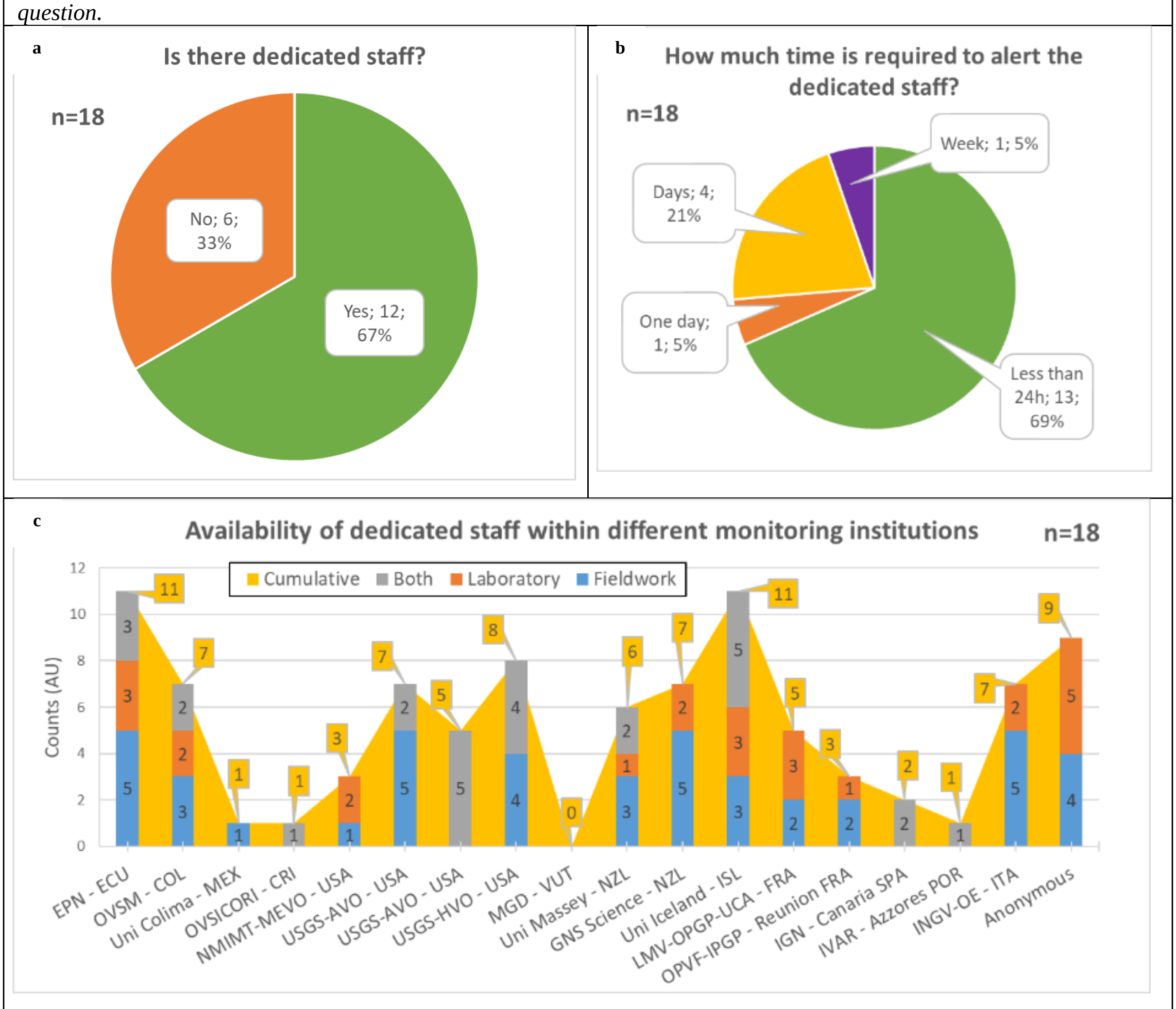
				2016-2017, Shishaldin 2019-20, Veniaminof 2018
Vanuatu (VUT)	GD	Vanuatu Meteorology and Geohazards Department - Geohazards Division	MGD	All Vanuatu volcanoes. Recent eruptions are 2017-2018 Ambae and 2018 Ambrym.
New Zealand (NZL)	A	Massey University - Volcanic Risk Solutions	Uni Massey	Contributes to monitoring Central Plateau volcanoes in the Southern Taupo Volcanic Zone in the event of volcanic crises, For example, 2012 Te Maari eruption, 2006-07 Ruapehu eruptions
New Zealand (NZL)	RI	Institute of Geological and Nuclear Science	GNS Science	All New Zealand volcanoes, including offshore islands. Notable eruptions are Ruapehu (1945-1996, 2007), Tongariro (2012), Whakaari/White Island (1979-2000, 2012,2013, 2016, 2019)
Italy (ITA)	RI	Istituto Nazionale di Geofisica e Vulcanologica - Osservatorio Etneo	INGV - OE	Eruptions of Etna (2001, 2002-03, 2004-05, 2008-09, 2011-12) and Stromboli (2002-03, 2007)
Iceland (ISL)	RI	Instutute of earth sciences, University of Iceland	Uni Iceland	All Icelandic volcanoes. Recent eruptions are Eyjafjallajökull 2010, Grímsvötn 2011, Holuhraun 2014-2015
France (FRA)	RI	Observatoire de Physique du Globe de Clermont-Ferrand - Laboratoire Magmas et Volcans - Université Clermont Auvergne	OPGC - LMV - UCA	Piton de La Fournaise, Mayotte (new submarine volcano) Stromboli 2008; 2011; 2016; Piton de La Fournaise (2014-on going); Mayotte 2018-on going
France – Reunion Island	A, RI	Institut de Physique du Globe de Paris - Observatoire Volcanologique du Piton de la Fournaise	IPGP - OVPF	Monitoring Reunion volcanoes (Piton de la Fournaise, Piton des Neiges, Mayotte) and Comoros Archipelago volcanoes (e.g. Karthala). All eruptions of Piton de la Fournaise since 1998; 2007 caldera collapse event; 2018 Mayotte submarine eruption
Spain (SPA) – Canary Island	GD	Instituto Geográfico Nacional - Observatorio Geofísico Central & Centro Geofísico de Canarias	IGN	Stratovolcanoes and monogenetic fields in the Canary Islands. Last eruption was the submarine Tagoro eruption (El Hierro, 2011)
Portugal (POR) – Azores Islands	A	Instituto de Investigação em Vulcanologia e Avaliaçõa de Riscos	IVAR	Azores volcanoes. The only eruption that occurred in the Azores in the last decades was the Serreta submarine eruption in 1998-2001
-	A	Anonymous interviewee	-	-

Section 2 – Staff

The availability of skilled human resources, among volcanologists, petrologists, geochemists and technicians for field and laboratory activities, and the time required to alert them in case of eruption are crucial elements to obtain petrological data over a timeframe short enough to be useful in a petrological monitoring perspective.

Among the eighteen responding institutions, 67% have dedicated staff to conduct petrological monitoring (Figure 2.2a), with an average of 5.2 persons for each institution. Most of the people are on duty for fieldwork whereas there is a shortage of people for lab work, which is mitigated by persons that are employed for both the activities (Figure 2.2c). The time required to alert dedicated staff is generally short, as 69% of the institutions are able to alert and get people operative in less than 24 hours, 5% of them require one day, and only 26% need more than one day (Figure 2.2b).

Figure 2.2 - Following figures are the output of the "Staff section". The pie-charts illustrate how many institutions have a dedicated team for petrological monitoring (a), and how much time is required to alert them to be operative (b). The histogram (c), which represent multiple-choice answers, illustrate the distribution of dedicated staff among the responding institution and what their duties are in fieldwork, laboratory work, or both. The number labelled within each histogram bar indicates the count of preferences for that specific class. The n value indicates the number of institutions that answered the question.



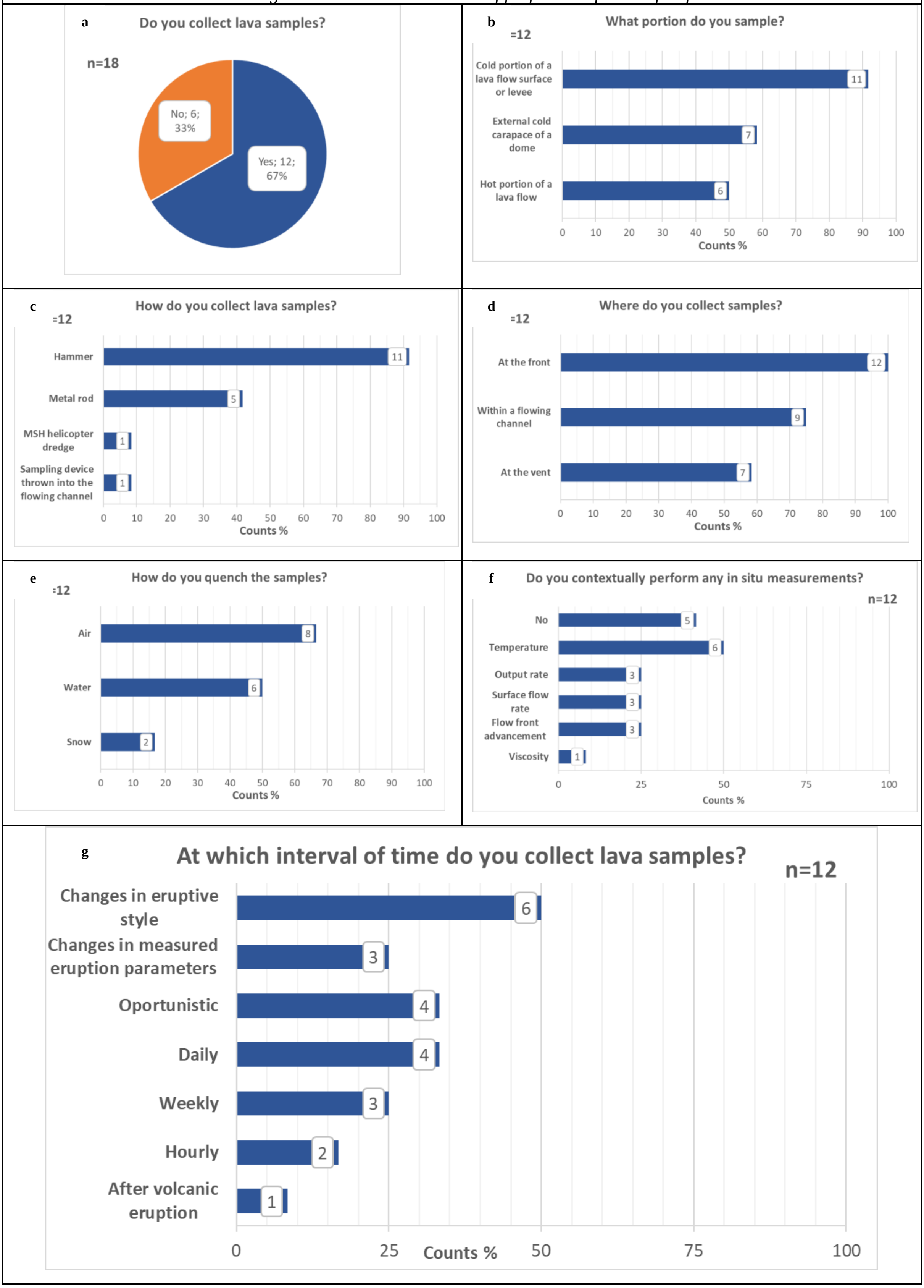
Section 3 - Lava sampling strategy

Sampling of lava (which includes lava flows and lava domes) is a common practice for 67% (12/18) of the interviewed institutions (Figure 2.3a), and among them the majority collect samples from a cooled lava flow (92%; 11/12) and from the external cold carapace of a dome (58%; 7/12), whereas only a minority (50%; 6/12) attempt the sampling of an active lava flow (Figure 2.3b). The rock hammer is generally used for lava sampling (92%; 11/12), a metal rod inserted in the hot lava (42%; 5/12) is the most used for the sampling of an active flow (Figure 2.3c), replaced in specific situations by a sampling device (like a hook) that is thrown into the flowing channel (8%; 1/12); helicopter dredges (8; 1/12) are used to scrape accretion dome spines (Figure 2.3c). The most common sampling location (Figure 2.3d) of a lava flow is at the front (100%; 12/12), however there is generally a good sample coverage along the flow with samples collected within flowing channels (75%; 9/12) as well at the vent (58%; 7/12). Most of the collected samples are usually cooled down in air (Figure 2.3e; 67%; 8/12), quenched in water (50%; 6/12) or alternatively in snow (17%; 2/12).

About the half of the operators (42%; 5/12) do not perform in situ measurements during sampling (Figure 2.3f), whereas most common measurements include temperature (50%; 6/12), velocity (output rate, 3/12; surface flow rate, 3/12; flow front advancement, 3/12; 25% each), and viscosity (8%; 1/12).

Time intervals among successive sampling episodes (Figure 2.3g) are connected to both changes in eruptive style (50%; 6/12) and measured eruption parameters (25%; 3/12) but are also related to the weather/environmental conditions (opportunistic, 33%; 4/12). Nevertheless, there are attempts to deal with fixed sampling schedule, which range from daily (33%; 4/12), to weekly (25%; 3/12) and hourly (17%; 2/12).

Figure 2.3 - Plots illustrate the results of the "Lava sampling strategy" section. The n value indicates the number of institutions that answered the questions. The pie-chart illustrates how many institutions deal with lava sampling. All the histograms answer specific questions related to lava sampling procedures and represent multiple-choice answers; the numbers labelled within each histogram bar indicates the count of preferences for the specific class.



Section 4 - Pyroclasts sampling strategy

Sampling of pyroclasts (which include fallout and pyroclastic density currents deposits) is a common practice for almost any institution (Figure 2.4a; 89%; 16/18). Sampling locations of fallout pyroclasts range from distal to proximal areas depending on the clast size (Figure 2.4b). In particular, bomb-sized pyroclasts are collected at locations proximal to the volcanic vent (15/16), lapilli-sized pyroclasts are collected both at proximal (14/16) and medial (9/16) locations, and ash-sized pyroclasts are collected anywhere from proximal to medial and distal locations (13/16, 12/16, 13/16, respectively). The 69% of interviewed institutions (11/16) sample fallout pyroclasts along traverses (Figure 2.4c).

Sampling techniques for bomb-sized pyroclasts (Figure 2.4d) include the random collection from a single layer/events (12/16; 75%), or the sampling of the bulk deposit (10/16; 62%), whereas it is an unusual practice to sieve the deposit in the field to find the dominant clast size (1/16; 6%). Hand collection and quenching of still-hot bombs (7/16; 44%) is not a common practice, thereby most of the samples cool down in air (Figure 2.4e; 10/16; 62%), and only a minority are quenched in water (6/16; 37%) or snow (2/16; 12%).

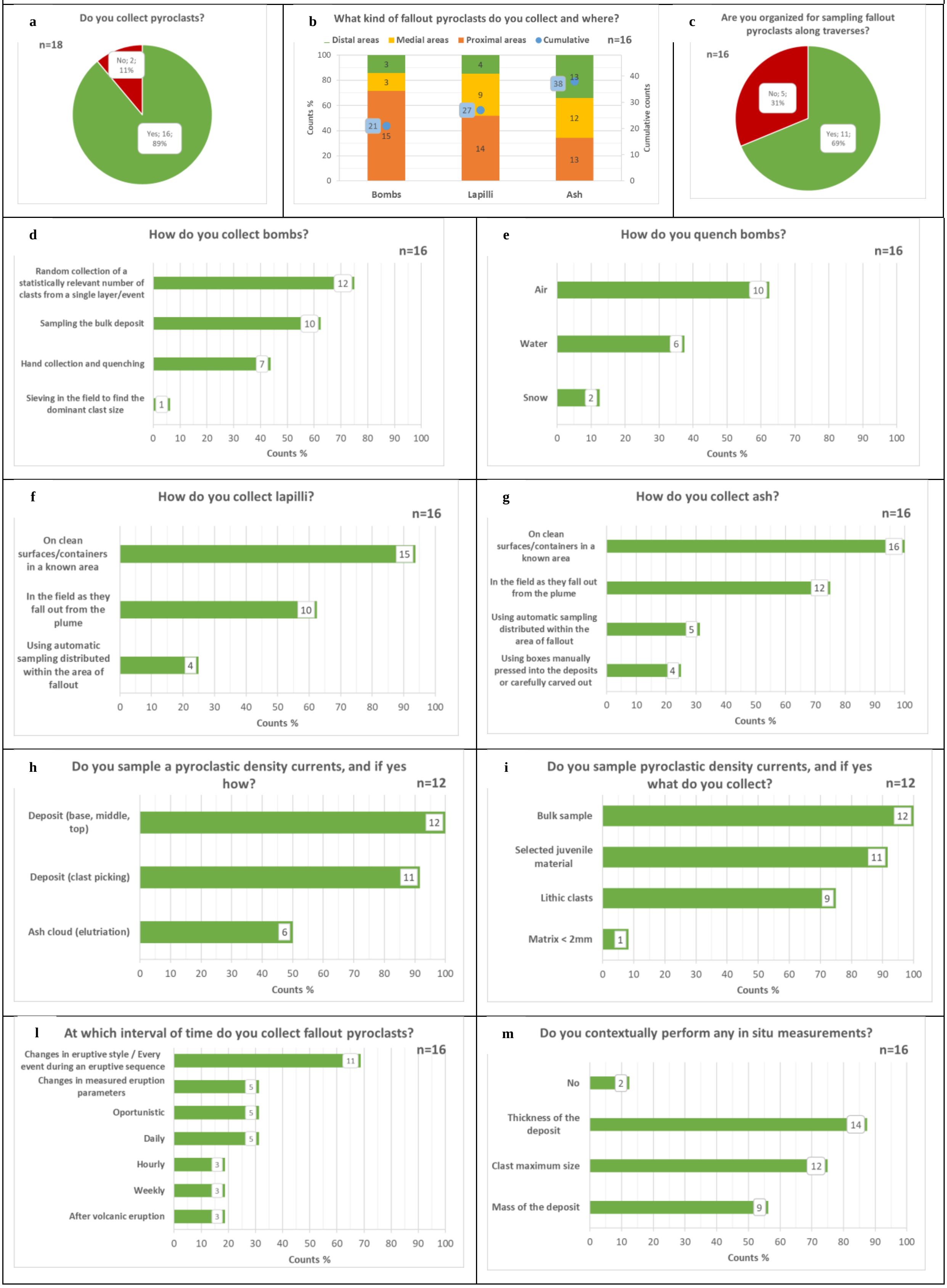
Sampling techniques for lapilli- and ash-sized pyroclasts (Figures 2.4f and 2.4g respectively) include different strategies varying from collection on free-surfaces (canvas or buckets) or from visually identifiable layers, as well as from individual layers separated by snow (15/16, or 94%, for lapilli and 16/16, or 100%, for ash), the collection as they fall out from the plume (10/16, 62%, for lapilli, 12/16, 75%, for ash), and the use of automatic sampling tools (e.g., ash meters) distributed in the area of fallout (4/16, 25%, for lapilli and 5/16, 31%, for ash). Another technique for ash sampling, which allows preservation of the layering, concerns the insertion of tubes (or boxes) manually pressed into (or carefully carved out of) the deposits (4/16; 25%).

Sampling of pyroclastic density currents is performed by twelve of the interviewed institutions. Sampling the different layers of the emplaced deposit following its internal (base, middle, top) structure is the unequivocal strategy (Figure 2.4h; 100%; 12/12), although clast picking is frequent for some specific purposes (92%; 11/12); less common is the sampling of the fallout material elutriated from the ash cloud (50%; 6/12). The sampling of pyroclastic density current focuses on bulk deposit (Figure 2.4i; 100%; 12/12), selected juvenile (92%; 11/12), and lithic clasts (75%; 9/12); it is uncommon to sample the matrix of finer than 2 mm (8%; 1/12).

Most of the operators perform in situ measurements during pyroclasts collection (Figure 2.4l) such as thickness (14/16; 87%), clast maximum size (12/16; 75%), and mass of the deposit (8/16; 50%).

Concerning the timing of sampling (Figure 2.4m), the situation remains similar to lava sampling, as sampling is subordinate to changes in the eruptive style (11/16; 69%) or in the measured eruption parameters (5/16; 31%) but is still opportunistic in relation to weather and access conditions (5/16; 31%). Attempts to deal with fixed sampling schedule persist, and sampling intervals range from hourly (3/16; 19%), to daily (5/16; 31%), and weekly (3/16; 19%).

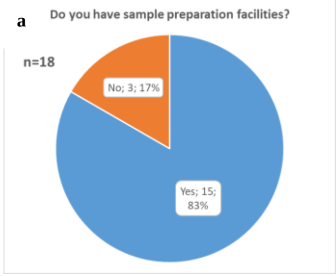
Figure 2.4 - Plots illustrate the results of the "Pyroclasts sampling strategy" section. The n value indicates the number of institutions that answered the question. All the histograms represent multiple-choice answers, and the numbers labelled within each histogram bar indicates the count of preferences for that specific class.

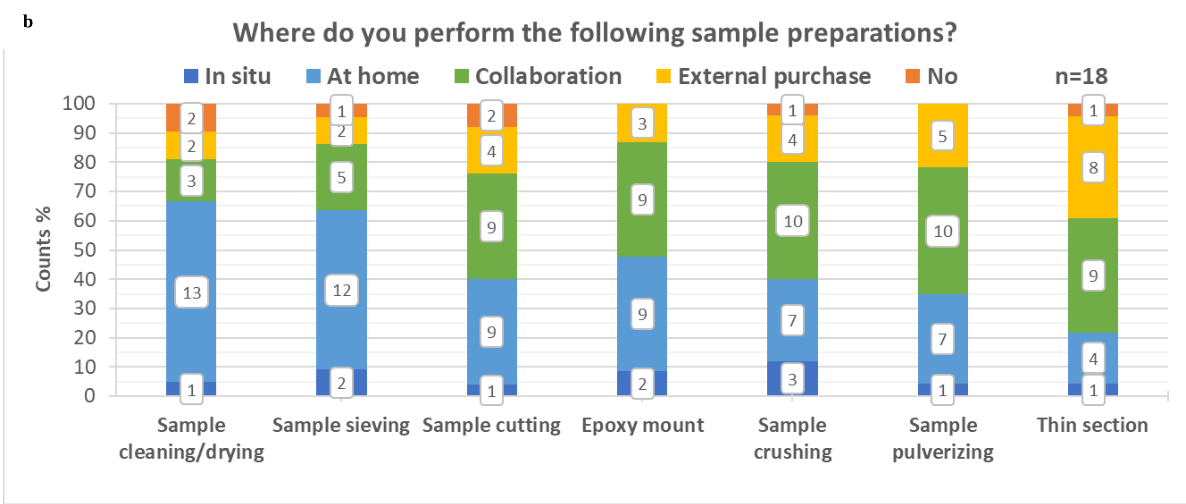


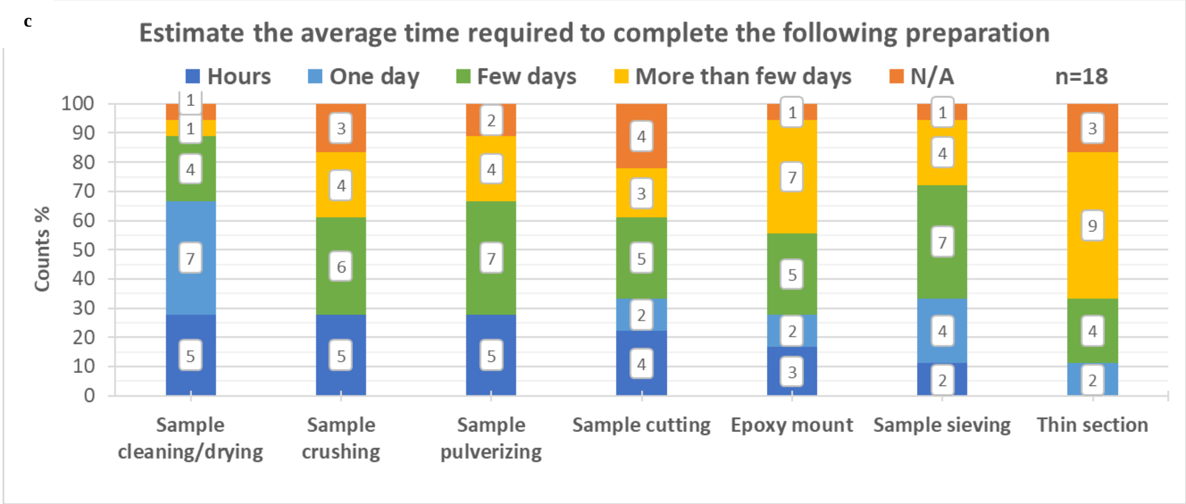
Section 5 – Sample preparation

Sample preparation is carried out prior to analytical procedures. It can be a time-consuming process, although with appropriate facilities and a standardized routine most of the preparation can be performed in a short time. The survey reveals that the 83% (15/18) of the interviewees has availability of sample preparation facilities within their home institution (Figure 2.5a). Basic operations such as sample cleaning/drying (72%) and sieving (67%) are generally performed at the home institution (Figure 2.5b), within a short time frame (hours 28% and one day 39% for cleaning/drying), or prolonged a time (few days 39% for sieving). Other procedures, such as sample cutting and preparation of epoxy mounts, are equally split among home and collaborating institutions (50% each), within the timeframe of days. Crushing, pulverizing, and thin-sectioning are generally performed in collaboration with external institutions (average of 50%) or upon payment (average of 33%) and could require a few days or more to be accomplished (Figure 2.5c).

Figure 2.5 - Plots illustrate the results of the "Sample preparation" section. (b) Illustrates the location where sample preparations are performed by the responding institutions. The keywords are defined as following: In situ, in the field, or very close to sampling locations (e.g. mobile lab); Home institution, in the observatory lab closest to the volcano; Collaborating institution, in the lab at another branch of your institution; External, a third-party institution that provides services for purchase. (c) Illustrates the average time required from the institutions to perform the sample preparations procedures.







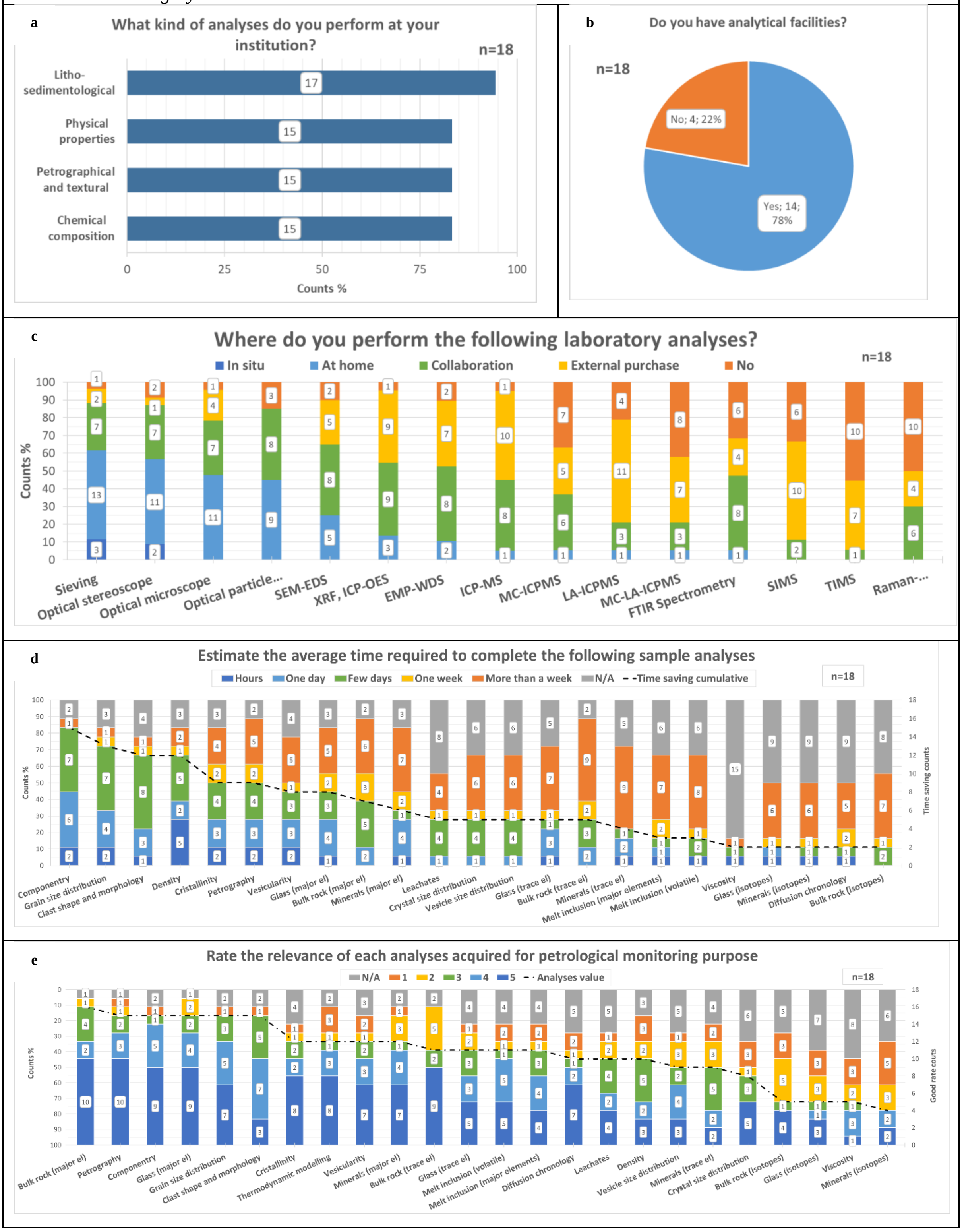
Section 6 – Laboratory analyses

Laboratory analyses are roughly divided into four groups related to the object of measurement: 1) physical properties; 2) litho-sedimentological features; 3) petrographical and textural features; 4) chemical composition. Survey results reveal that all of them are performed by the interviewed institutions (Figure 2.6a; 15/18, 17/18, 15/18, and 15/18 respectively).

Most of the interviewed institutions (78%; 14/18) have analytical facilities within their home institution (Figure 2.6b). Equipment for litho-sedimentological and textural investigations, such as sieves, optical stereoscopes and optical microscopes, are generally owned by the institutions (Figure 2.6c) and allow to steadily accomplish most of the essential analyses (e.g., grain size distribution, componentry, clast shape and morphology, petrography, crystallinity, vesicularity) in a timeframe ranging from hours to few days (Figure 2.6d). Performance of more detailed textural and chemical investigations usually involves collaborating institutions (e.g. Scanning Electron Microscope - Energy Dispersive X-ray Spectroscopy (SEM-EDS); Electron Microprobe - Wavelength-Dispersive X-Ray Spectroscopy (EMP-WDS); X-ray Fluorescence Spectroscopy (XRF); Inductively coupled plasma atomic emission spectroscopy (ICP-AES); optical particle measurements; Figure 2.6c) or external ones by purchasing (e.g., Multicollector and Laser Ablation Inductively Coupled Plasma-Mass Spectrometry (MC and LA -ICP-MS); Secondary Ion Mass Spectrometry (SIMS); Thermal Ionization Mass Spectrometry (TIMS), Figure 2.6c). Clearly, the involvement of away-from-home institutions implies increase in the time needed to obtain analytical results (Figure 2.6d). The survey displays that some analyses can be performed in a short time, ranging from few days to a week (e.g., major elements composition of bulk rock, glasses, and minerals, and crystals and vesicles size distribution; Figure 2.6d), others require more than a week to be accomplished (e.g., trace elements, isotopic, and melt inclusions composition, and diffusion chronology; Figure 2.6d).

The rating of relevance for the proposed analyses (Figure 2.6e) highlight that the scientific community consider litho-sedimentological, petrographical and textural features (e.g., componentry, crystallinity, vesicularity), together with major element geochemistry (on glass, bulk rock and minerals), the most valuable data for petrological monitoring purposes. Other analyses, obtained from technologically advanced investigations, such as isotope and trace elements geochemistry, melt inclusion geochemistry, crystal and vesicle size distributions, are less relevant for petrological monitoring purposes.

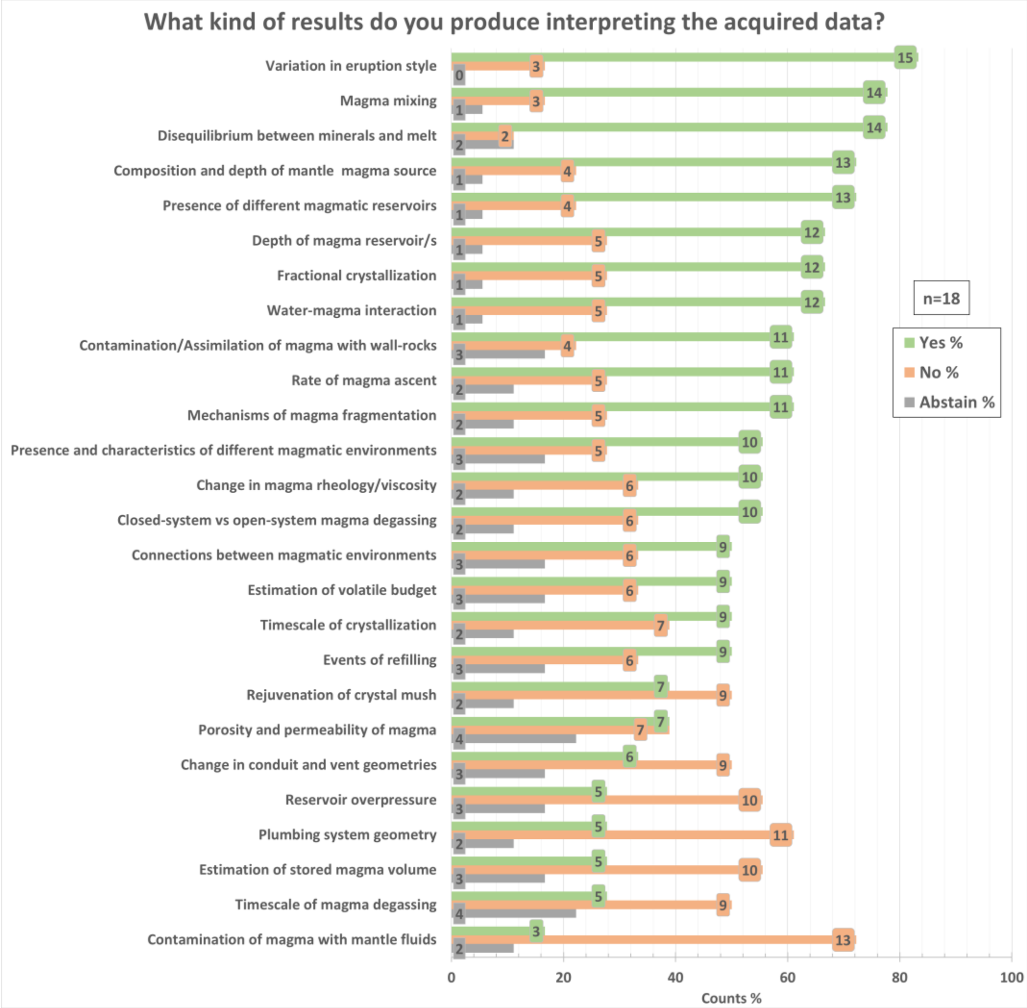
Figure 2.6 - Plots illustrate the results of the "Laboratory analyses" section. (c) Illustrates the location where laboratory analyese are performed by the responding institutions; the keywords in situ, home, collaborating and external institutions are the same defined in figure 2.5. (d) Illustrate the average time required for the institutions to perform the analytical procedures; dotted line is a threshold that separate fast analyses (high value of the threshold) from slow analyses (low value of the threshold). (e) Illustrate the rating of petrological analyses on a scale of 1 to 5 (where 1 is poor relevance, 5 is high relevance) for monitoring purposes; the dotted line is a threshold that separates good-rated analyses (high value of the threshold) from poor-rated ones (low value of the threshold). Numbers in white boxes represent the number of answers in the category.



Section 7 – Data results and collaboration with other monitoring scientists

Figure 2.7 illustrates the most common interpretations produced by the combination of the petrological results discussed in the previous section. Among the possible interpretations, the most valuable in the framework of petrological monitoring are about (1) eruptive behaviour (e.g., variation in the eruptive style, water-magma interaction, and mechanisms of magma fragmentation), gathered from integration of litho-sedimentological and textural analyses, (2) processes occurring in the plumbing system, which are determined from the geochemical and textural results (e.g., magma mixing, disequilibrium between minerals and melt, and fractional crystallization), and (3) insight about the architecture of the plumbing system itself (e.g., presence of magmatic reservoir and their depths), inferred from geochemistry, textures and petrological modelling. Other processes occurring in the plumbing system concerning magma dynamics (e.g., rate of magma ascent and closed-system vs open-system magma degassing, events of refilling) and physical properties (e.g., change in magma rheology/viscosity, timescale of crystallization, estimation of volatile budget, contamination and assimilation with wall-rock) have an average ranking. The least ranked products include those results that are more difficult to address, even though some of them would be crucial for petrological purposes (such as, rejuvenation of crystal mush, change in plumbing system, conduit and vent geometries, estimation of stored magma volume), and those related to the mantle magma source (e.g., composition and depth of mantle source and contamination with mantle fluids) that are less relevant in a monitoring perspective.

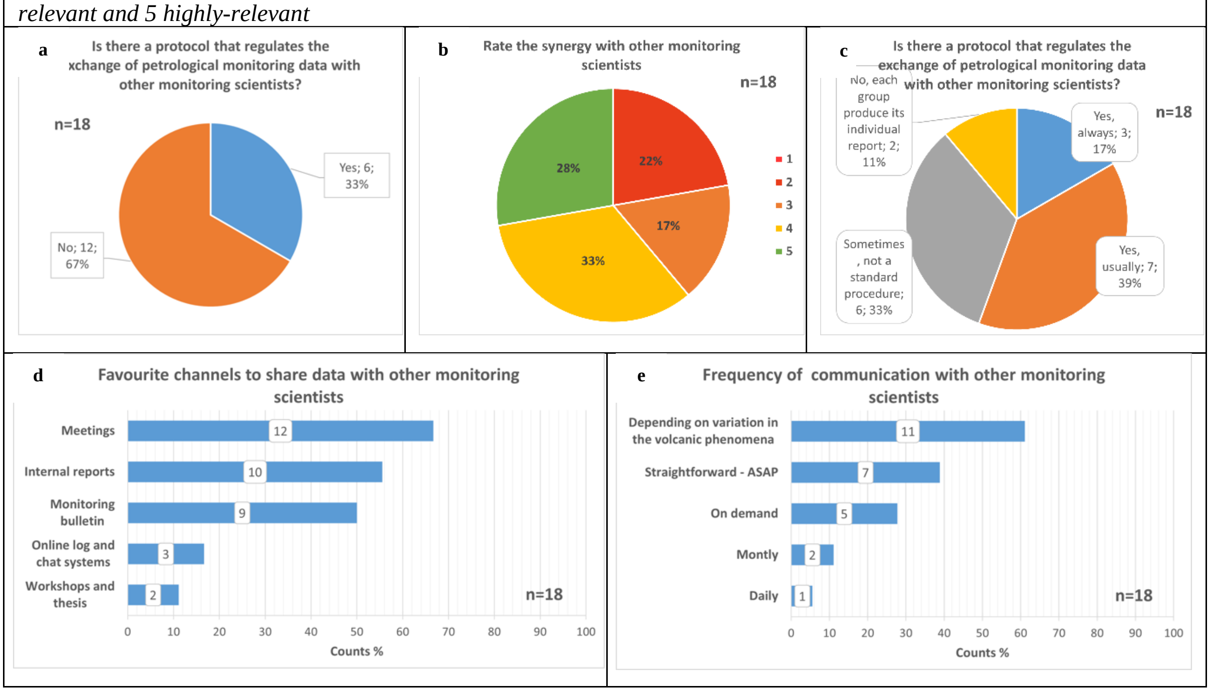
Figure 2.7 - Ranking of the most common interpretations produced by the combination of petrological data. The n value indicates the number of interviewees. The numbers on histogram bars indicate the preference counts.



The survey also highlights the perception that a great advancement in monitoring volcanic activity would be achieved by the combination of data acquired within different disciplines, like seismology, geodesy, gas geochemistry and petrology, to depict a comprehensive scenario. Despite this, monitoring institutes generally do not have protocols to regulate the exchange of information among scientist of different disciplines (Figure 2.8a), and even though the synergy among different groups is overall well rated (Figure 2.8b), the production of multidisciplinary reports is not a consolidated practice (Figure 2.8c).

Furthermore, the survey highlights that the channels of communication between monitoring scientists include live meetings (either in person, by phone or video-streaming), internal reports or monitoring bulletins (Figure 2.8d). Also, the frequency of communication mostly depends on the variation of the volcanic activity, and it is straightforward during intense phases of activity, but there is a lack of exchange of data during ordinary phases (Figure 2.8e).

Figure 2.8 - Plots illustrate the results of the "Collaboration with other monitoring scientists" section. The n value indicates the number of institutions that answered the question. Values within pie charts and histograms indicate the number of preferences for each category and the related percentage. The 1 to 5 scale in panel (b) relate to the rating, being 1 poorly-relevant and 5 highly-relevant



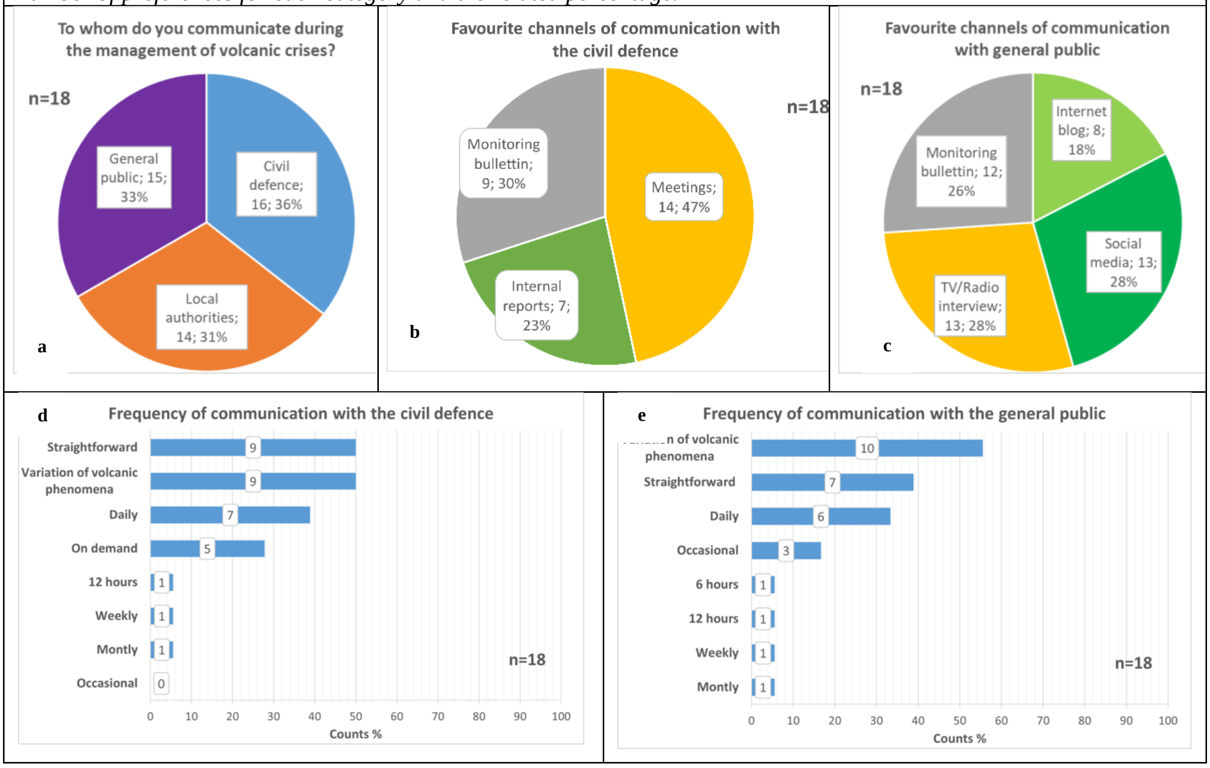
Section 8 – Data dissemination with authorities and general public

Communication of data outside the scientific community is an important duty. Recipients are the authorities in charge of the crisis management and the population that need to be informed of the situation and should be trained to react at different alert levels. Recipients of information are almost equally divided (Figure 2.9a) among civil defence (36%), local authorities (31%) and general public (33%).

Major communications channels among scientists and authorities (Figure 2.9b) are meetings (47%), followed by monitoring bulletins (30%) and internal reports (23%). The frequency of communication with civil defence (Figure 2.9d) is tightly regulated and depends on the volcanic activity, and it may be either straightforward or on demand. However, daily checks appear to be frequent as well.

Favourite communication channels with the general population are interviews, monitoring bulletins, social media and internet blogs (Figure 2.9c). The frequency of communication with the general public also depends upon the type of volcanic activity, and it is straightforward or daily during impacting eruptions, otherwise it would be occasional (Figure 2.9e).

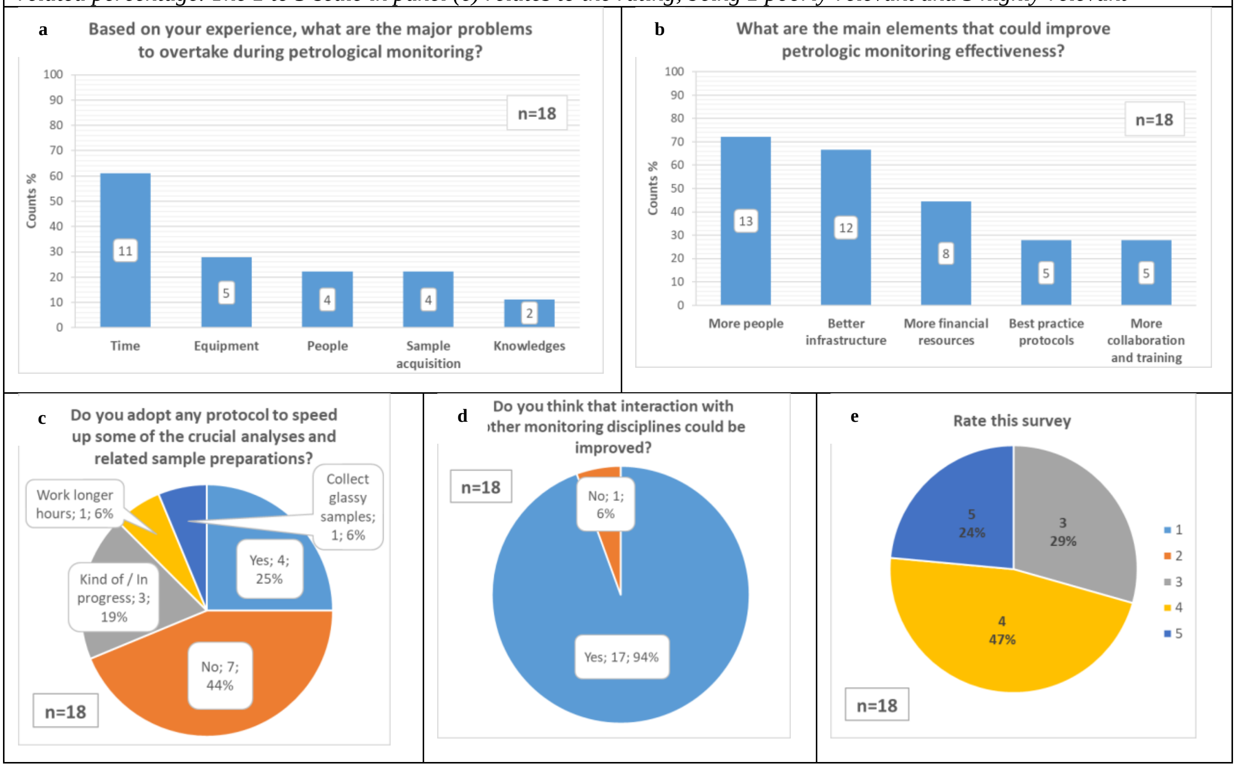
Figure 2.9 - Plots illustrate the results of the "Data dissemination with authorities and general public" section. The n value indicates the number of institutions that answered the question. Values within pie charts and histograms indicate the number of preferences for each category and the related percentage.



Section 9 – Conclusion

The last section of the survey includes open-ended questions focused on collecting opinions related to possible improvements of petrologic monitoring procedures. The main problem to address is the rapid response to accomplish a specific task related to monitoring procedures (Figure 2.10a). Other recurrent issues include the lack of equipment and of skilled people, and lastly minor problems concern sample acquisition and lack of knowledge (Figure 2.10a). Elements that could improve the effectiveness of petrological monitoring are the employment of more skilled people and better infrastructure and facilities, which both depend on a higher availability of financial resources (Figure 2.10b); other elements that would improve petrological monitoring are the lack of best practice protocols, better collaboration with other scientists, and more training.

Figure 2.10 - Plots illustrate the results of the "Conclusion" section. The n value indicates the number of institutions that answered the question. Values within pie charts and histograms indicate the number of preferences for each category and the related percentage. The 1 to 5 scale in panel (e) relates to the rating, being 1 poorly-relevant and 5 highly-relevant



Discussion

The collected information results from a sample of eighteen interviewed institutions, which roughly represent 20% of worldwide volcano observatories. Although this institution sample is not representative of the whole community that is responsible for volcano monitoring, it adequately represents the portion that deals with petrologic monitoring as it includes the majority of the active volcanic provinces worldwide, with only a few countries absent, like Indonesia, Philippines, Africa (e.g., Ethiopia, Congo, etc..), Papua New Guinea and Japan. Also, the responding institutions offer insights into volcanoes with a variety of volcanic activity and of magma composition, providing a comprehensive picture of the state of the art of petrological monitoring. For the above reasons we consider the following discussion highly representative of possible issues related to petrological monitoring of volcanoes.

The survey pointed out the main difficulties to be overcome in order to have a profitable petrological monitoring structure, which include (i) the time expenditure to accomplish both field survey and laboratory works (sampling, preparations and analyses), (ii) the lack of *on-site* facilities and infrastructures, (iii) the shortage of qualified staff, and (iv) the non-ideal cooperation among monitoring scientists of different disciplines. Some specific issues are evaluated in detail in the following and subsequently, starting from this set of problems raised by the survey, there is a proposition for definition of best practices in petrological monitoring.

Issue #1 - Sampling

Petrological monitoring methods study the solid products erupted during volcanic activity; therefore, the fundamental requirement is the availability of a good set of samples, representative of the magma that feeds the eruption. For this purpose, samples have to be carefully selected among fresh and unaltered materials and, if possible, the collection of early-quenched glassy samples is preferable when magmatic pre-eruptive processes are considered, since features related to post-eruptive and emplacement processes are avoided. This also provides the opportunity to finalize the analyses for the acquisition of both bulk rock and glass compositions.

Moreover, the possibility to have a time-zero sample, which represents the beginning or the opening phases of the eruption, provides several advantages as it provides (i) the immediate comparison with previous eruptions and related eruptive styles, (ii) early hints about magmatic and volcanic processes responsible for the eruption, including the possible trigger, and (iii) the capability to (possibly) know the nature of magma prior to the climax of the eruption and to track deviations over its course. These benefits are crucial in the case of reactivation of quiescent volcanoes.

Another major challenge of the sampling operations concerns the fact that operators work in a hostile environment, during ongoing eruptions, on rugged topography, with severe weather conditions, and sometimes in remote locations. For these reasons field surveys need to be well-planned, so that the optimal sampling target can be promptly identified, and the task safely and rapidly accomplished.

Sampling strategy is obviously related to the type of volcanic activity. As a general rule, lava flows are sampled within 5-10 km from the vent, whereas explosive eruptions, which are very dangerous at proximal locations, offer the opportunity to collect the ash fractions at a safe distance away (from tens to hundreds of km away from the volcanic source).

Issue #2 - Laboratory activities

A compelling need is to organize local volcanic observatories and monitoring institutions in a safe area immediately close to a volcano with facilities that allow the institutions to carry out fundamental core analyses in a short (quasi real-time) timeframe. These would be the "first-aid" analyses, valuable during syn-eruptive phases, which cannot be endangered by practical and logistical challenges.

The aim of best practice protocols is to highlight which are the most suitable investigations, in terms of costs versus benefit (e.g., time and resource expenditure vs value of the obtained result), to prioritize for successful petrological monitoring. In the following sections, based upon the survey results, we are going to propose our suggestions for best practice procedures together with the construction of a realistic workflow that includes adequate techniques to operate in the case of effusive and explosive eruptions.

Issue #3 - Lack of financial resources, people or infrastructure

Petrology, together with geophysics, geodesy and gas geochemistry, should play a primary role in the operating procedures of volcano monitoring. A desirable outcome of this work would be an augmented perception of the benefits that petrologic monitoring brings in the comprehension of eruptive processes.

In particular, monitoring teams should recognize that petrological monitoring is the only "network" that provides signals (i.e. rock samples) concerning the magma. In addition information on the magma are provided even when other monitoring signals (e.g seismic or ground deformations) are poorly informative (e.g., during the stationary state of long eruptions). This acknowledgment should lead to better planning of petrological monitoring activities, focused on the recognition and the fulfilment of the primary needs, being either infrastructure, dedicated facilities or human resources.

Issue #4 - Poor cooperation among monitoring scientists
The survey highlights that the synergy among different monitoring scientists is moderate. The whole community feels that increasing cooperation and exchange of data would represent a great improvement for monitoring science. This should be encouraged, not only during eruptive phases, but especially during period of quiescence, to build up solid background knowledge and trust relationships among scientists of different disciplines.

Suggestion for "Petrological Monitoring Best Practices"

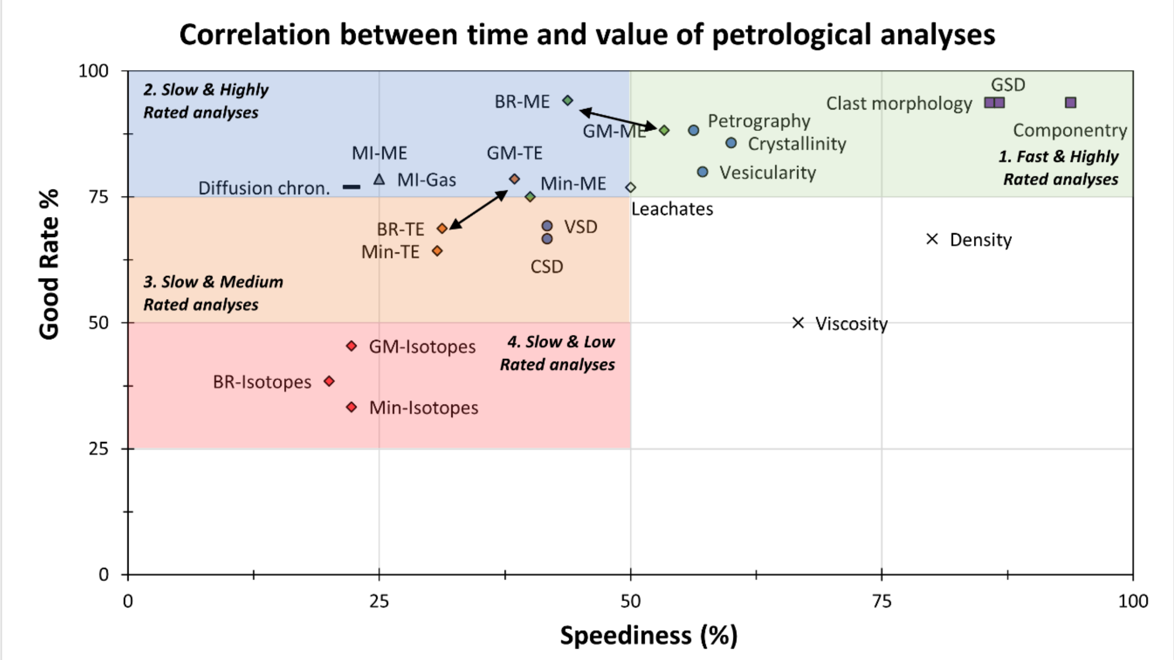
Based on the above considerations, an important aspect for efficient petrological monitoring is to issue broadly accepted protocols of best practice based on the balance between those analyses that are fast and easy to acquire (in terms of resources/equipment availability and time) and the relevance of their results for the monitoring purpose.

In the survey we asked responders to rate on a 1 to 5 scale, the relevance of each analysis for petrological monitoring purposes (the N/A option was suggested for those analyses that are not performed). To summarize the data, we computed the sum of high-rated values (ranks 3, 4 and 5) for each analysis, and the resulting coefficient is plotted as a threshold in Figure 2.6e. This coefficient, which would represent the "good-rated" analyses, is used to calculate the "Good rate %" by dividing it by the count of preferences for each analysis (see Table 3 in Appendix; N/A counts are excluded by the computation). The same operations have been performed to summarize the data for the average time required to perform each analysis (Figure 2.6d), and a "Speediness %" value has been calculated from the sum of preferences for fast analyses (we consider analyses performed in a timeframe of hours, one day and few days to be fast; see Table 4 in Appendix).

Rate% and Speediness% are correlated in an X-Y plot (Figure 2.11). In this plot, an arbitrary threshold of 75% on rating (y-axis) identifies the most profitable analyses for petrological monitoring, and we assume that all the analyses plotted above this threshold (Figure 2.11; green and blue field) represent the hard-core practices of petrological investigations. Indeed, the interpretation of these data provide the most powerful petrologic information that would be advantageous for any research institution. Similarly, we set in the diagram another arbitrary threshold, located at 50% of the speediness (x-axes), above which are plotted all the fastest analyses (Figure 2.11).

This method allows us to identify four quadrants. Inside the green box of Fig. 2.11 are plotted the fast and highly rated analyses (above 75% rating and 50% speediness, respectively). We suggest that best practices for syn-eruptive petrological monitoring should necessarily include this set of analyses. In detail, the bare minimum includes: litho-sedimentological (componentry, grain size distribution and clast morphology) and textural (petrography, crystallinity and vesicularity) investigations of products, together with major element glass geochemistry (for pyroclast) and bulk rock (for lavas). Most of these analyses are highly valuable, fast to accomplish and low cost, as they can be performed with basic and cheap equipment such as sieves, stereoscopes and microscopes. With the exception of glass geochemistry which requires more expensive instrumentation (e.g., SEM-EDS), all these analyses can be performed within the observatory infrastructure and not far from monitored volcanoes, possibly even in mobile labs. Major element bulk rock geochemistry, which falls in the blue field immediately outside the 50%-time barrier, deserves a special mention. Similar to glass geochemistry, it requires dedicated expensive instruments (e.g., XRF or ICP), and it is also a bit more time consuming for sample preparation procedures; nevertheless, it is sometimes the only option to gather chemical information (e.g., depending on the nature of the sample). For the above reasons, analyses in the green box include classical volcanological and petrological investigations and represent the essential set that must always be performed during petrological monitoring of an eruption. Their accomplishment could be fast if appropriate procedures are standardized (see Figure 2.12).

Figure 2.11 - Correlation between speediness and relevance of main petrological investigations. Acronyms: BR-bulk rock; GM-glass matrix; Min-minerals; MI-melt inclusions; ME-major elements; TE-Trace elements; GSD-grain size distribution; VSD-vesicle size distribution; CSD-crystal size distributions. Legend: Cross-physical properties; Squares-lithosedimentological analyses; Circles-textural analyses;diamond-geochemistry; triangles-melt inclusions; Dash-diffusion chronology. N.B.: data for viscosity are not statistically significant as it has high % of abstained.



Interpretation of the data acquired with the essential techniques provides crucial information on ongoing volcanic and magmatic processes; for example, litho-sedimentological techniques can give insights into explosive eruptions, such as variation of eruptive style, mechanism of magma fragmentation, and magma-water interaction. Textural and geochemical analyses allow us to understand magmatic processes occurring in the shallow plumbing system such as refilling, mixing of different magmas, disequilibrium conditions of mineral growth, the presence of different magmatic reservoirs, and so on.

Among the analytical techniques that fall in the blue field (Figure 2.11; highly rated but slower analyses) diffusion chronology is the most promising technique since it allows us to make correlations between magmatic processes inferred from petrologic data and real-time monitoring signals (e.g., geophysical). However, the accomplishment of this technique is presently highly consuming in term of resources and time, as it requires high-tech facilities and an articulated post-sampling procedure that consists of multiple steps of sample preparation and analyses (see Deliverable 10.1).

All the analyses that fall in the orange and red boxes (Figure 2.11) give very powerful petrological information but are generally expensive and require more time to be acquired; these data are excellent for extended petrological investigations, for assessing background condition, or for long term variation of the magmatic processes within the monitored volcanoes. However, if there are conditions to accomplish these analyses in a short time, they could well be of use during syn-eruptive monitoring. White box analyses are rarely performed, however density and viscosity are really useful for modeling lava flow.

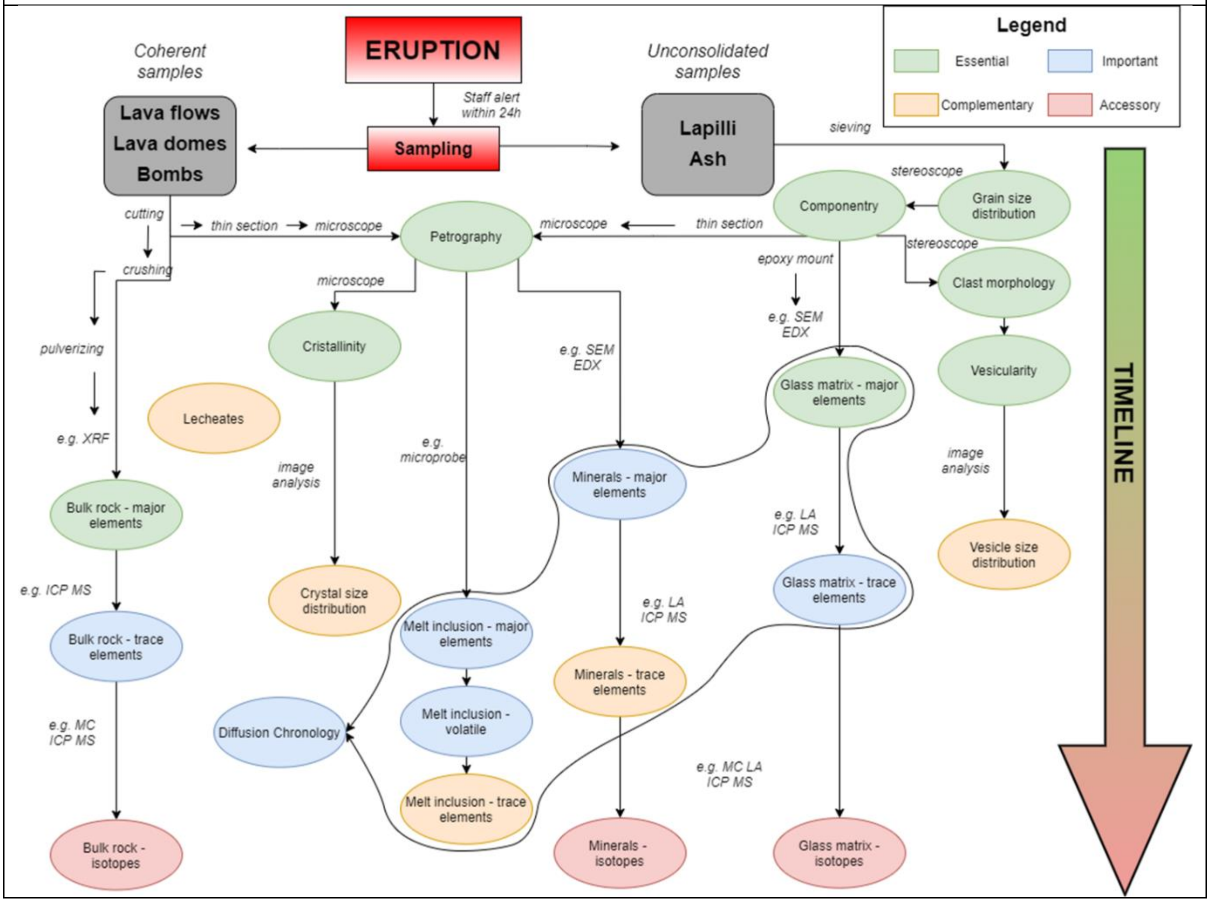
Based on the above considerations we propose here a flow chart describing best practices for petrological monitoring (Figure 2.12). We have divided the flow chart into two branches based upon the nature of the sample, coherent and unconsolidated, as they require different preparation procedures. Moreover, the partition between coherent and unconsolidated samples also reflects (1) the sampling location; the former are collected near the vent, the latter at medial and distal locations, and (2) the type of eruption, as the former (bombs excluded) represent effusive eruptions, whereas the latter are representative of explosive ones.

The first manipulation of coherent samples is cutting. Subsequently, thin sectioning is required for textural investigation (petrography, crystallinity and vesicularity), whereas crushing and pulverizing are preliminary tasks for bulk rock geochemistry.

On the other hand, the preparation of unconsolidated samples involves sieving (for grain size distribution), and identification and separation of components. Once the juvenile fraction is recognized epoxy mounts (or thin sections) are moulded for textural investigation (clast shape, petrography, crystallinity and vesicularity) and microprobe glass geochemistry.

These essential analyses can be extended with quantitative textural investigations (e.g., via image analyses), detailed geochemistry (minerals and melt inclusions composition, trace elements and isotope geochemistry) and diffusion chronology.

Figure 2.12 – Workflow for petrologic monitoring best practices. Essential analyses are highly advised for syn-eruptive monitoring, followed by important analyses for more detailed investigations. The curved lines that point to diffusion chronology embrace the whole set of preliminary investigations to achieve this result.



Conclusion

The survey submitted to eighteen worldwide institutions that deal with petrological monitoring, and the detailed analysis of answers received, highlight the major issues that affect the accomplishment of petrological monitoring practices during ongoing eruptions. Major concerns are the time expenditure to accomplish both field survey and laboratory work (sampling, preparation and analyses), that are related to the lack of facilities, infrastructure (or financial resources in general) and the shortage of qualified staff to accomplish specific tasks.

The survey also gave insight into the essential procedures to be perform in the framework of syn-eruptive petrological monitoring. The identified best practices are the best compromise between the analyses that are fast and easy to acquire (in terms of resources/equipment availability and time) and the relevance of the results in terms of valuable information during eruptive crises.

The scientific community should endorse the essential role of petrology, together with other monitoring disciplines, in the operative procedures during syn-eruptive monitoring, filling a gap in the primary needs by providing dedicated infrastructure, facilities and human resources.

3) Assessment of ^{226}Ra-^{210}Pb-^{210}Po radioactive disequilibria and volatile accumulation before recent eruptions, and integration with deformation

Volatiles play a major role in driving volcanic eruptions and their exsolution at depth, either in closed- or open-system, will ultimately control how explosive lava emission at the surface might be. In addition to the physics of the degassing process itself, its duration is also a key parameter to be determined. Radioactive disequilibria among U- and Th-series isotopes have proved efficient for setting time constraints on magmatic processes, including degassing processes (e.g., Gauthier and Condomines, 1999). For instance, recent work on the Eyjafjallajökull eruptive sequence (Sigmarsson et al., 2015) suggests that the ^{226}Ra-^{210}Pb-^{210}Po disequilibria measured in fresh lavas record the degassing history of the magmatic system several months to years prior to the eruption. This geochemical dataset is best explained by gas accumulation in a shallow reservoir, which ultimately triggered the eruption and might account for observed surface deformation (Sigmarsson et al., 2015).

In comparison to studies dealing with radioactive disequilibria in lavas, less attention has been paid so far to disequilibria in the gas phase released at active volcanoes, which is in striking contrast with the two following observations. First, gases are much more mobile than silicate liquids and they may reach the surface prior to lava. Therefore, any attempt to use geochemical data as predicting tools for monitoring active volcanoes should better rely on gas analyses. Second, it is now well established that short-lived radioactive disequilibria between radon daughters (^{210}Po-^{210}Bi-^{210}Po) in volcanic gases bring key constraints for determining shallow magma dynamics at active volcanoes, namely the magma residence time in shallow reservoirs and the transfer time of gases from the reservoir to the surface (Gauthier et al., 2000).

A recent theoretical model suggested however, that the radioactive noble gas ^{222}Rn – in spite of its short half-live of only 3.8 days – plays a major role on controlling observed disequilibria (Terray et al., 2018). While radon is commonly monitored in soils and fumarolic discharges at active volcanoes, little attention has been paid so far to its concentration (or activity) in the primary magmatic vapor released at open vent degassing volcanoes. Within the framework of the EuroVolc project, we therefore conducted pioneering studies in order to measure ^{222}Rn in magmatic gases and relate its activity to those of its long-lived daughters in order to shed light on the dynamics of degassing processes at Mount Etna, Sicily. Achieving this goal requires being able to decipher the many sources of radon (atmosphere, soil degassing, fumarolic discharges) contributing to its budget in addition to the primary magmatic vapor, enhance the signal-to-noise ratio of radon measurements, and finally produce high-frequency datasets.

A passive radon dosimetry experiment was first conducted for 5 months at Mount Etna in order to derive a cartography of radon emissions from the Central Craters. Passive dosimeters were set on thirty monitoring stations around the Bocca Nuova + Voragine rim, with one dosimeter at ground level and a second one at one meter above the ground (Terray et al., 2020a). They show that the radon degassing budget in both the highly hydrothermalized southern edge of Bocca Nuova and the fractured northeastern sector of Voragine is mostly controlled by soil degassing (Figure 3.1, left). In marked contrast, the southeastern sector of Bocca Nuova, located under the dominant wind and therefore mostly under the gas plume influence, shows high radon activity at 1m meter above the ground, which makes it the first direct evidence of high radon enrichments in Etna magmatic gases, up to 550 Bq/m3 (Figure 3.1, right).

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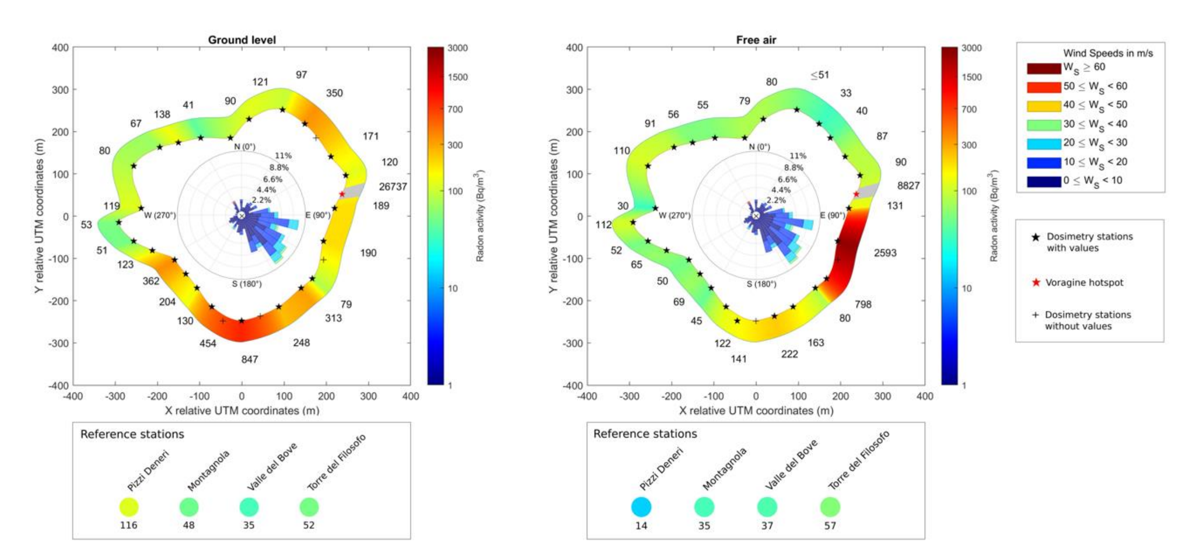
Figure 3.1: Radon activity in air at the summit of Mount Etna revealed by passive dosimetry at ground level (left) and one meter above ground level (right). Radon levels are represented as a color-ring (vertical scale on the right side of the two charts) and the wind regime is given as a wind rose (Terray et al., 2020a).



Most importantly, radon activity in the SE sector appears to peak at high values during a period of volcanic unrest starting during the summer 2018, which suggests that radon activity in air could be routinely monitored in Volcano Observatories as an additional geochemical parameter. However, passive dosimetry has a too-long response time (about two months of exposure to gas is required) to be of use for this purpose. Electronic radon dosimeters with a 6-hour integration time and communicating through an IoT Lorawan protocol show however, than they could give reliable radon results and be deployed at low-cost on active volcanoes, although further testing must be carried out beyond this initial proof of concept (Terray et al., 2020b).

In addition to the previous methods based on direct analysis of ^{222}Rn, UCA developed a brand-new field spectrometer (named RAVIOLI, for Radon Analysis on Volcanoes with In-situ Observation of short-Lived Isotopes) in order to analyse radon in volcanic gases with an unprecedented accuracy by measuring its first short-lived isotopes (^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po) based on their α or β decay (Terray et al., in prep.). The primary magmatic vapor has not been characterized yet, mostly due to difficult sampling conditions over the last field campaigns. Nonetheless, we have been able to characterize the radon background in the summit crater atmosphere as resulting from a mixture of tropospheric air (low radon activity in equilibrium with its daughters) and soil gases (high radon activity without daughter products, these latter being adsorbed in the soil along the diffusive degassing path of radon) (Terray, 2021). The use of this device also allowed determination of physical interactions between both solid matter (e.g., filters and membranes used in volcanic aerosol sampling) and radioactive α particles, which may lead to a significant decrease in α counting efficiency (Terray et al., 2021, in rev.). This metrological advance is a major step towards more accurate characterization of radioactive disequilibria in volcanic gases and therefore, better knowledge of the dynamics of degassing processes as derived from mathematical models.

All taken together, these pilot studies suggest that radioactive disequilibria among radon and its daughters in volcanic gases make a robust geochemical tool for better understanding degassing processes and eruptive activity at active volcanoes. While analyses of the whole Rn-series requires time-consuming measurements that might be hardly reconciled with operative duties in observatories, radon monitoring in air at selected sites on degassing volcanoes could be envisaged for predicting changes in eruptive activity. However, there are still many steps to be undertaken from these early proofs of concept to an operative monitoring system and we encourage volcano observatories to contribute to advances in this field.

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Appendix

In this appendix are included Tables 3 and 4, that summarize the results of the survey concerning the rate of relevance and the time expenditure for laboratory analyses. In these tables is also calculated the coefficient used to make comparison among these parameters.

The survey itself can be accessed in the Google doc at https://forms.gle/8i4Z8bFAjvLrLD8d8

Table 3 – Survey result for question in the section 6 „Rate the relevance of each analysis for petrological monitoring purposes". This data are plotted in Figure 2.6e. The table also illustrates the value of the threshold plotted in figure 2.6e and the Rate% value of figure 2.11

	RATING								
	N/A	1	2	3	4	5	Sub. TOT	GOOD RATE coeff	GOOD RATE%
Bulk rock (major el)	1	0	1	4	2	10	17	16	94,12
Clast shape and morphology	2	1	0	5	7	3	16	15	93,75
Componentry	2	1	0	1	5	9	16	15	93,75
Grain size distribution	2	1	0	3	5	7	16	15	93,75
Glass (major el)	1	0	2	2	4	9	17	15	88,24
Petrography	1	1	1	2	3	10	17	15	88,24
Crystallinity	4	1	1	2	2	8	14	12	85,71
Vesicularity	3	2	1	2	3	7	15	12	80
Glass (trace el)	4	1	2	3	3	5	14	11	78,57
Melt inclusion (major elements)	4	2	1	3	4	4	14	11	78,57
Melt inclusion (volatile)	4	2	1	1	5	5	14	11	78,57
Diffusion chronology	5	2	1	1	2	7	13	10	76,92
Leachates	5	1	2	4	2	4	13	10	76,92
Minerals (major el)	2	1	3	1	4	7	16	12	75
Vesicle size distribution	5	1	3	2	4	3	13	9	69,23
Bulk rock (trace el)	2	0	5	2	0	9	16	11	68,75
Crystal size distribution	6	3	1	3	0	5	12	8	66,67
Density	3	3	2	5	2	3	15	10	66,67
Minerals (trace el)	4	2	3	5	2	2	14	9	64,29
Viscosity	8	3	2	1	3	1	10	5	50
Glass (isotopes)	7	3	3	1	1	3	11	5	45,45
Bulk rock (isotopes)	5	3	5	1	0	4	13	5	38,46
Minerals (isotopes)	6	5	3	0	2	2	12	4	33,33

Table 4 - Survey results for questions in section 6 „Estimate the average time required to complete the following sample analyses“. These data are plotted in Figure 2.6d. The table also illustrates the value of the threshold plotted in figure 2.6d and the Speediness% value of figure 2.11

	TIME								
	Hours	One day	Few days	One week	More than a week	N/A	Sub. TOT	Speediness Coefficient	Time%
Componentry	2	6	7	0	1	2	16	15	93,75
Grain size distribution	2	4	7	1	1	3	15	13	86,67
Clast shape and morphology	1	3	8	1	1	4	14	12	85,71
Density	5	2	5	1	2	3	15	12	80
Viscosity	1	0	1	0	1	15	3	2	66,67
Crystallinity	2	3	4	2	4	3	15	9	60
Vesicularity	2	3	3	1	5	4	14	8	57,14
Petrography	2	3	4	2	5	2	16	9	56,25
Glass (major el)	1	4	3	2	5	3	15	8	53,33
Leachates	0	1	4	1	4	8	10	5	50
Bulk rock (major el)	0	2	5	3	6	2	16	7	43,75
Crystal size distribution	0	1	4	1	6	6	12	5	41,67
Vesicle size distribution	0	1	4	1	6	6	12	5	41,67
Minerals (major el)	1	4	1	2	7	3	15	6	40
Glass (trace el)	1	3	1	1	7	5	13	5	38,46
Bulk rock (trace el)	0	2	3	2	9	2	16	5	31,25
Minerals (trace el)	1	2	1	0	9	5	13	4	30,77
Melt inclusion (major elements)	1	1	1	2	7	6	12	3	25
Melt inclusion (volatile)	1	0	2	1	8	6	12	3	25
Diffusion chronology	1	0	1	2	5	9	9	2	22,22
Glass (isotopes)	1	1	0	1	6	9	9	2	22,22
Minerals (isotopes)	1	0	1	1	6	9	9	2	22,22
Bulk rock (isotopes)	0	0	2	1	7	8	10	2	20