Chapter 2

Studying Volcanic Plumbing Systems – Multidisciplinary Approaches to a Multifaceted Problem

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Additional information is available at the end of the chapter

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Abstract

Magma transport and storage beneath active volcanoes occurs in the so-called volcanic plumbing system (VPS), a network of different magmatic sheet intrusions and magma reservoirs. The complex physical and chemical processes, which occur in the volcanic plumbing system, are key parameters that control the occurrence of an eruption, as well as type and size of the eruption. It is therefore imperative to assess plumbing system processes and their dynamics. Traditionally, plumbing system research is done as a part of various scientific disciplines, each with its own research questions, methods, and terms. As a consequence, there is often little overlap and communication between the disciplines. In this chapter, we give an overview of the history of plumbing system research and outline the state of the art of the main scientific disciplines involved. We summarise the potential and limitations of each discipline and then discuss three key components to foster multidisciplinary research—namely communication, information, and education—which are essential to promote a better understanding of the complexity of volcanic plumbing systems.

Keywords: volcanic plumbing system, magma transport, magma storage, multidisciplinary research, volcanology

1. Introduction

Volcanic plumbing systems (VPS) form a plexus of magma channels and reservoirs that are governed by complex interactions of chemical and mechanical processes that control how magmas are emplaced and how they propagate through the Earth's crust to an eventual eruption (**Figure 1**; [1]). Volcanic plumbing systems thus set the stage for volcanic eruptions and govern the style and magnitude of eruptive activity including dramatic volcano–tectonic phenomena, such as caldera and sector collapses.

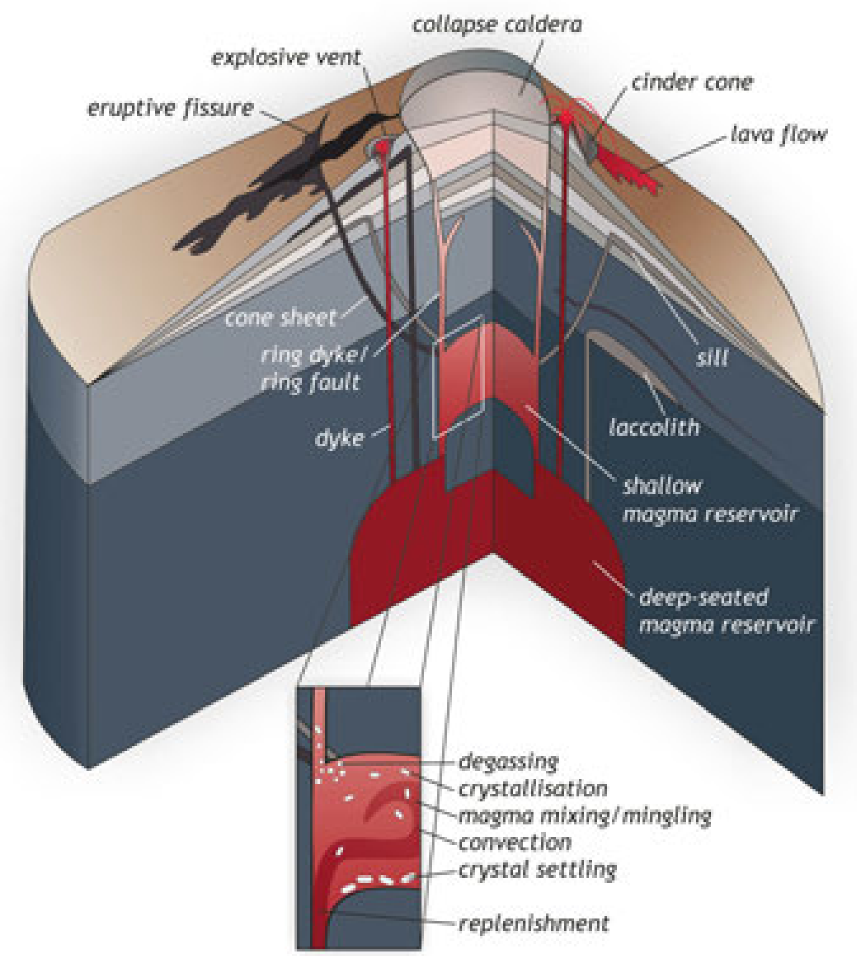

Figure 1. Schematic sketch of different components of volcanic plumbing systems, highlighting the complexity of the different types of magma channels and reservoirs. The inset illustrates the processes that may occur within magma bodies.

Traditionally, however, the study of the plumbing system components, such as dykes, sills, and larger magma bodies (**Figure 1**), as well as their dynamics is strongly method-based, for example, focussing exclusively on the composition of plutonic bodies or the seismicity of magma ascent. To date, relatively few bridges between the distinct disciplines exist. In this chapter, we will give a short overview of the historical development of the main concepts on volcanic plumbing systems and the diversification of research disciplines that study plumbing systems. We then proceed to outline the aims and approaches, as well as the potential and limitations, of the main disciplines, namely field and structural analysis, igneous petrology and geochemistry, geophysics, geodesy, and modelling. We will then discuss challenges and opportunities of combining approaches from different disciplines to overcome some of the limitations and contribute to a better understanding of the complex and dynamic processes within active volcanoes.

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2. History of the study of volcanic plumbing systems

While naturalists of the eighteenth century debated the origin of basalt, James Hutton was the first to propose that dykes and sills formed by the solidification of "subterraneous lava" and that even granite was once in a molten state [2]. Hutton's views were based on meticulous field observations of magmatic intrusions exposed at the Earth's surface. Performing one of the first systematic petrological experiments, Sir James Hall [3] delivered supporting evidence by melting and cooling volcanic glass and basalt to produce a variety of crystallinity in the experimental products.

By the time the first petrological classifications of igneous rocks had been established and microscopy and experimental petrology had started to emerge as distinct approaches in the second half of the nineteenth century, field mapping had become more focused on the shapes and structures of igneous intrusions [4]. Studies of igneous rock bodies from that time added laccoliths [5], batholiths [6], and other intrusion geometries to the previously described dykes, veins, and sills. Based on his observation of deformation in the rocks surrounding igneous intrusions in the Henry Mountains in Utah, Gilbert [5] started to study the mechanics of magma emplacement to unravel why magma at some occasions gets trapped in the crust or erupts at other occasions. In the following decades, researchers such as Daly [7] found evidence for different types of magma emplacement mechanisms. These mechanisms were gradually linked to specific types of intrusive bodies, a classification of which was established in the early twentieth century [8]. By this time, field observations in the eroded volcanic complexes of the British Isles had identified ring dykes and cone sheets as specific intrusion types [9, 10].

Petrologists of the early twentieth century focused in turn on fractional crystallisation and magma differentiation in sills and layered intrusions [11–14]. Hence, from the first half of the twentieth century, field-based research concerning volcanic plumbing systems was conducted in parallel as part of the disciplines of igneous petrology, structural geology, and volcanic geology, as well as by distinct communities studying granitic plutons, fossil subvolcanic complexes, and extrusive rock suites in volcanic areas.

The second half of the twentieth century saw major advances in the understanding of volcanic deposits and eruptions, as well as how these are linked to the underlying volcanic plumbing system. One of the most influential researchers of this time is George P. L. Walker who, together with his students, and based on systematic observations and quantitative mapping of extinct volcanic complexes in the British Isles and Eastern Iceland, fundamentally advanced our understanding of magma transport in dykes and the architecture of shallow magma plumbing systems in central volcanoes [15, 16].

Apart from the subdiscipline of experimental petrology, even other types of modelling have been employed to study volcanic plumbing systems. Analogue modelling (or laboratory modelling) of intrusive and volcanic processes became an increasingly important method (see Section 3.5), particularly after Hubbert [17] and later Ramberg [18, 19] had introduced the principle of scaling to ensure similarity between geological and model systems [20]. Numerical modelling of plumbing systems, on the other hand, is rooted in the analytical solutions of mostly fluid-dynamic and stress-field problems within classical structural geology. Development of computer software that is often originally designed for materials science simulations and the ever increasing computational capacity have led to a boost in numerical modelling studies of—among many other Earth science topics—volcanic plumbing systems.

The second half of the twentieth century was also the beginning for geophysical studies of volcanic plumbing systems. While gravimetric methods are nowadays routinely applied to study granitic plutons and subvolcanic complexes [21, 22], geophysical monitoring techniques have become a standard in active volcanic areas (see Section 3.3). In addition, since the launch of satellites and satellite-based mapping of the Earth's surface in the 1960s, geodesy has become an increasingly popular method to infer processes related to magma transport in active volcanoes (see Section 3.4).

The history of plumbing system research reflects the methodological and conceptual development and diversification of the Earth sciences in general. Since the days of the early naturalists who described natural phenomena as a whole, our understanding of volcanic plumbing systems has deepened considerably. However, at the same time, as we started to dig deeper into specific aspects, we mostly lost our view of the big picture. Currently, volcanic plumbing system research is carried out in the disciplines of igneous petrology, structural geology, volcanology, geophysics, and geodesy, employing methods such as field mapping, major and trace element analysis, seismology, analogue modelling, and interferogrametry of radar measurements from satellites. Section 3 gives an overview of the state of the art of the most important approaches.

3. Methods commonly used to study volcanic plumbing systems

3.1. Field geology and structural analysis of volcanic plumbing systems

Field based studies of volcanic plumbing systems have initially aimed at a qualitative description of intrusive phenomena and focused on a classification of intrusion lithologies and morphologies to understand how magma is transported, stored, and evolves in the crust [23]. With time, field work has become increasingly quantitative, producing a detailed record of the compositions and structures associated with magmatic intrusions [24]. Analyses of the composition, absolute and relative ages, and dimensions of the components of magmatic plumbing systems have produced a more and more systematic view of the emplacement and evolution of plumbing systems [25, 26]. Besides the recording of variations in lithology and emplacement-related structures, mapping of magmatic intrusions often includes the study of magmatic fabrics recorded within the igneous rocks [27], such as preferred orientation of phenocrysts and of magnetic minerals using their so-called anisotropy of magnetic susceptibility (AMS; [28, 30]). Recently, classical methods, such as field mapping with paper maps and compass, have become complemented by modern digital mapping techniques using global positioning system (GPS) and smart phones (**Figure 2**). At the same time, the possibilities to analyse structural data collected in the field become more and more sophisticated. In addition to thorough statistical analysis and stereographic projection [31, 32], three-dimensional (3D) structural modelling is used to visualise, reconstruct, and interpret structural field data [33–35].

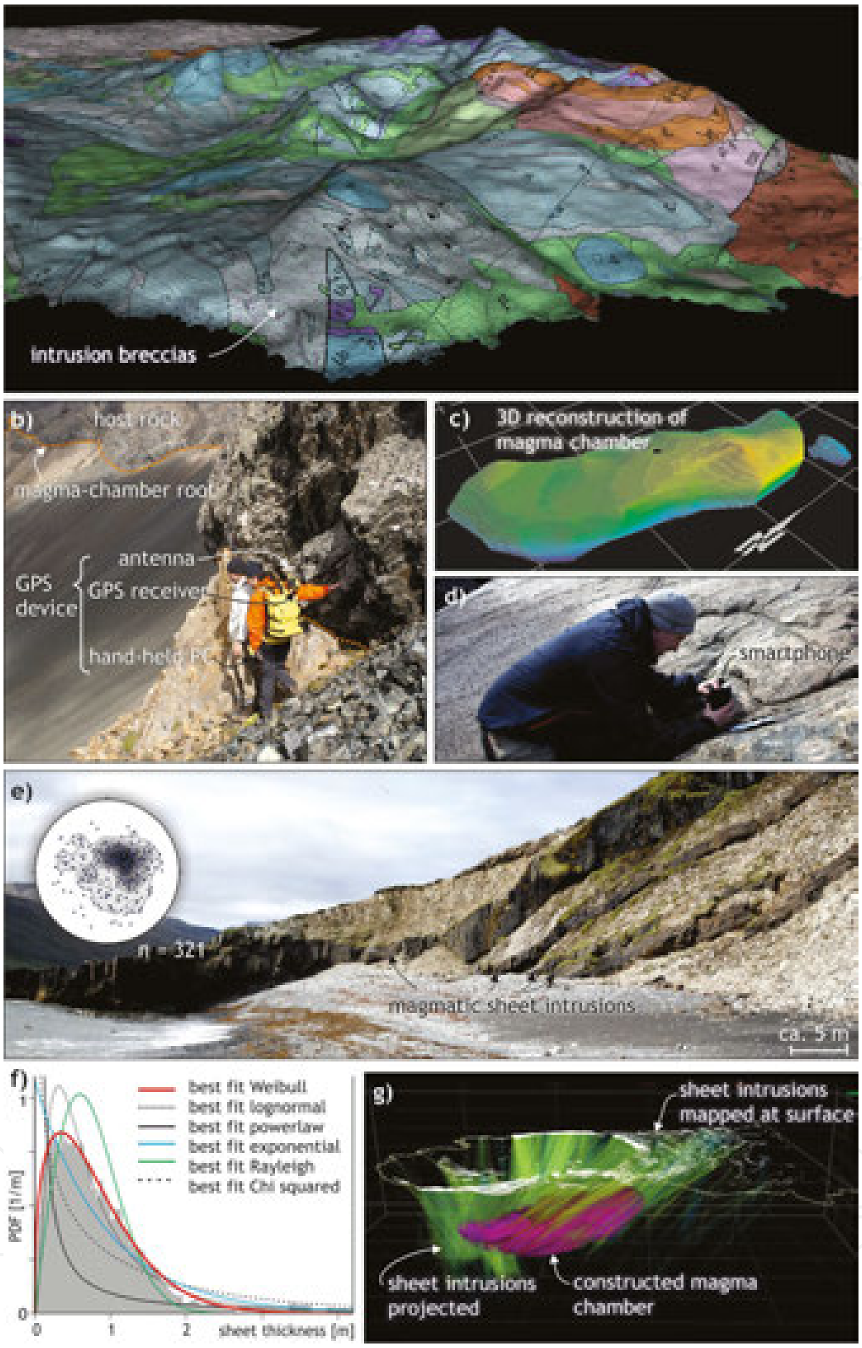

Figure 2. Examples of field and structural studies of volcanic plumbing systems. (a) Geological map of the Isle of Rum draped over a Digital Elevation Model. Map modified from Scottish Natural Heritage 1:20,000 map; © SNH. (b) High-precision GPS mapping of the roof of a granitic pluton (cf. [40, 41]). (c) Result of 3D reconstruction of a granitic pluton based on GPS mapping. (d) Measuring fractures in a granitic intrusion using a smart phone and Field Move Clino app by Midland Valley Ltd. (e) Outcrop of basaltic inclined sheets and corresponding projection of poles to orientation planes and density of 321 such sheet intrusions in an equal area, lower hemisphere plot (cf. [42]). (f) Probability Density Function (PDF) of the thickness of magmatic sheets, such as shown in (e) compared to a selection of statistical distributions. (g) 3D structural model of the plumbing system of the Ardnamurchan central complex, Scotland, produced using Move by Midland Valley Ltd (modified from [34]).

Igneous plumbing systems in outcrops regularly extend over several kilometres. Such wide extents represent a substantial challenge for (1) having a correct overview understanding of the structure of the exposed VPS and (2) completing structural field surveying in a manageable time. In addition, numerous field areas of interest are hardly reachable for direct observations, such as very steep mountains and crevasses. Recent technologies, including LiDAR scanners, drones, and robots, have recently started overcoming these challenges. The one hand, LiDAR scanners have been used to produce high-precision and high-resolution textured virtual outcrop models [36]. Such digital models allow detailed, quantitative 2D and 3D fracture mapping of extensive, mostly subvertical outcrops [37]. On the other hand, drone surveys combined with photogrammetric tools are very helpful to produce virtual outcrop models and orthorectified images of extensive subhorizontal or gently dipping outcrops, and provide new observational perspectives for extensive structural mapping [38]. Finally, robots equipped with monitoring tools can explore the Earth's interior that is inaccessible for humans [39]. The data produced by these modern tools allow new possibilities for post-field digital mapping of extensive areas, thus shortening the field campaigns.

Therefore, field studies of exhumed plumbing systems form the foundation of our conceptual understanding of the individual components of volcanic plumbing systems, their morphologies, sizes, and emplacement mechanisms, as well as of characteristic structures in the host rock associated with the evolution of magmatic intrusions. Field work in eroded volcanic areas is therefore of critical importance, because it provides us with fundamental information that may be used to benchmark numerical and laboratory models (see Section 3.5) and to interpret geophysical and geodetic data (see Sections 3.3 and 3.4).

The main limitation of the field-based approach to study volcanic plumbing systems is that fossil and eroded volcanic plumbing systems represent a snapshot of the final state of the magmatic system only, while active volcanoes do not permit a detailed look inside their VPS. An outcrop in an eroded volcano is essentially a snapshot of the sum of all superimposed processes a suite of rock has experienced. It is thus not always straightforward to extract accurate age relationship between individual units or even distinct boundaries at times, as well as to deduce what dynamic processes were contributing to the final picture.

3.2. Petrological and geochemical studies of volcanic plumbing systems

Igneous petrology and geochemistry are among the classic approaches used to characterise volcanic plumbing systems (see also Section 2) and aim to describe the conditions, time scales, and characteristics of the chemical evolution of magma. This characterisation is generally based on the mineralogy and textures of igneous rocks, as well as their major and trace element composition (e.g. **Figure 3**). In order to study the minerals, textures, and compositions of rock samples collected in the field, igneous petrologists employ a wide range of analytical techniques, which have been developed simultaneously with, and strongly facilitated, an increasing understanding of the chemical evolution of minerals and melts. These analytical techniques have emerged in a rapid succession and have become increasingly precise since igneous petrology was established as a discipline and the first microscopes were built in the second half of the nineteenth century (see Section 2). Today, rock textures and the type and associations

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of minerals in thin sections of rock samples are studied using a variety of microscopes. The bulk, or whole-rock, composition of an igneous rock that mostly comprises the quantity of major elements or their oxides can be derived through, for example, exposing a powdered sample of a rock to X-rays (X-ray fluorescence (XRF)). Other analytical techniques, such as mass spectrometry, can quantify the isotopic composition of the major and trace elements of a sample.

Data on the mineralogy and composition of igneous rocks are probes into the chemical evolution of volcanic plumbing systems and can be used in many ways. In many cases, the whole-rock composition is characteristic of the geodynamic setting and origin of a magma and can also be used to discriminate processes in the plumbing system, such as fractional crystallisation (e.g. [43, 44]). The concentration of trace elements can be used in geochemical modelling to quantify processes in the volcanic plumbing system, such as assimilation of country rocks into the magma (e.g. [45]). The decay of radiogenic isotopes is used as a standard tool to determine the absolute age of a rock sample, which has led to detailed insights into the time scales of magma emplacement in volcanic plumbing systems (e.g. [46]).

At the scale of individual crystals, crystal size distributions, chemical zoning, and textures can serve as records of the chemical and thermal evolution of their host magmas (e.g. [47–49]). Crystal growth rates and chemical diffusion across crystal zones can furthermore be used to quantify the time scales of, for example, magma storage or replenishment (e.g. [50]). Moreover, pressure and/or temperature dependent mineral compositions can be used as so-called geobarometers and/or geothermometers that reveal the depth and conditions at which certain minerals grew, which usually corresponds to magma reservoir depths (e.g. [51, 52]).

In order to quantify the chemical evolution of minerals and magmas *in situ*, petrological experiments are used to simulate, for example, the influence of pressure and/or temperature on mineral compositions [53] and the reaction of magma with crustal rocks [54, 55].

Petrological and geochemical studies of volcanic plumbing systems are thus the foundation of our understanding of the chemical and thermal processes during magma storage and offer insight into the time scales of magma transport and evolution. Estimates of the depth of magma storage provide valuable constraints on the interpretation of geodetic and geophysical monitoring data of active volcanoes (see Sections 3.3 and 3.4). Furthermore, a characterisation of the types of magma erupted from a volcano and an understanding of the processes of magma evolution in the plumbing system allow evaluating the probable type of eruption in the future.

The main limitation of the petrological and geochemical approaches is that magma samples from active volcanic plumbing systems are generally not available. Although many of the processes of magma evolution can be constrained based on petrological experiments, the major and trace element compositions of rocks and minerals can in many cases not be attributed to any specific process. The contribution of each individual process is often difficult to quantify. Moreover, the insights derived from petrological and geochemical approaches apply to the geological past of the plumbing system only. It is therefore not always straightforward to conclude on the present state.

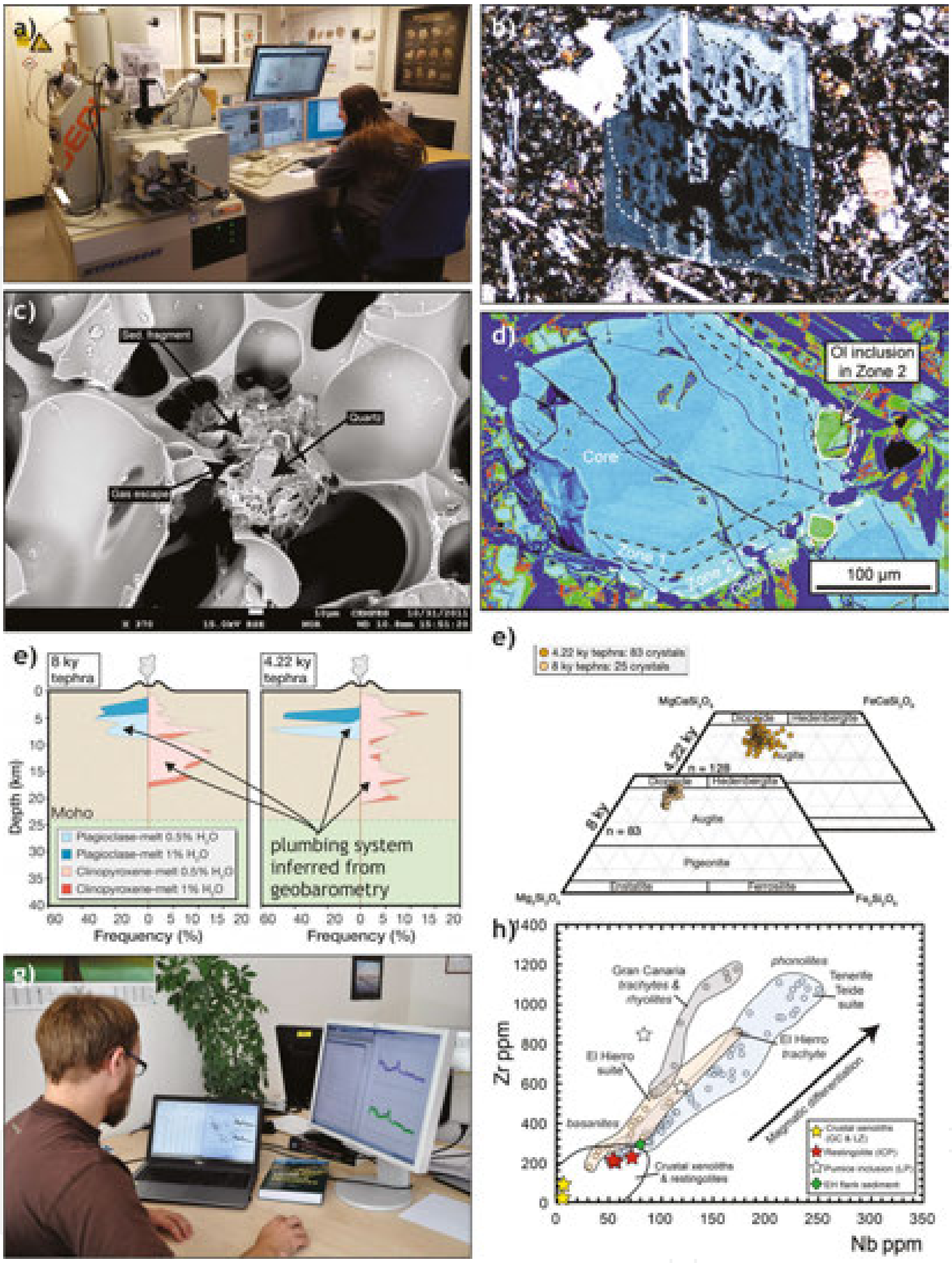

Figure 3. Examples of petrological and geochemical studies of volcanic plumbing systems. (a) High-precision chemical analysis and element mapping using a field emission gun electron probe microanalyser. (b) Thin section of a zoned plagioclase crystal (zonation indicated by dashed line) in basalt of the 2015 Holhraun eruption. Crossed polars. Crystal ca. 1 mm across. Crystal textures can be used to reconstruct processes in the volcanic plumbing system [57]. (c) Scanning electron microscope (SEM) image of vesiculated xenolith erupted offshore El Hierro [56]. (d) False-colour SEM image of a zoned clinopyroxene crystal in lava erupted at Holuhraun, Iceland. Zones and inclusions can be used to reconstruct processes in the volcanic plumbing system [58]. (e) Results of geobarometric modelling of plagioclase and clinopyroxene in tephras from Katla volcano, Iceland [58]. (f) Mineralogy of pyroxene crystals in Katla tephras [58]. (g) Analysing trace-element contents in igneous rocks. Image courtesy of Christophe Galerne. (h) Zr versus Nb plot of igneous rocks and xenoliths from the Canary Islands, Spain. Trace element compositions can be used to understand the origin of, and relationships between, rock groups [56].

3.3. Geophysical studies of volcanic plumbing systems

Geophysical studies of volcanic plumbing systems employ a variety of methods (**Figure 4**) that detect and quantify either the physical properties of different geomaterials, such as magma versus solid rock or igneous versus sedimentary rocks, or the effects of active physical processes, such as seismicity caused by the movement of magma through the crust. Geophysical methods are therefore applied to study both active volcanoes and extinct subsurface or eroded plumbing systems.

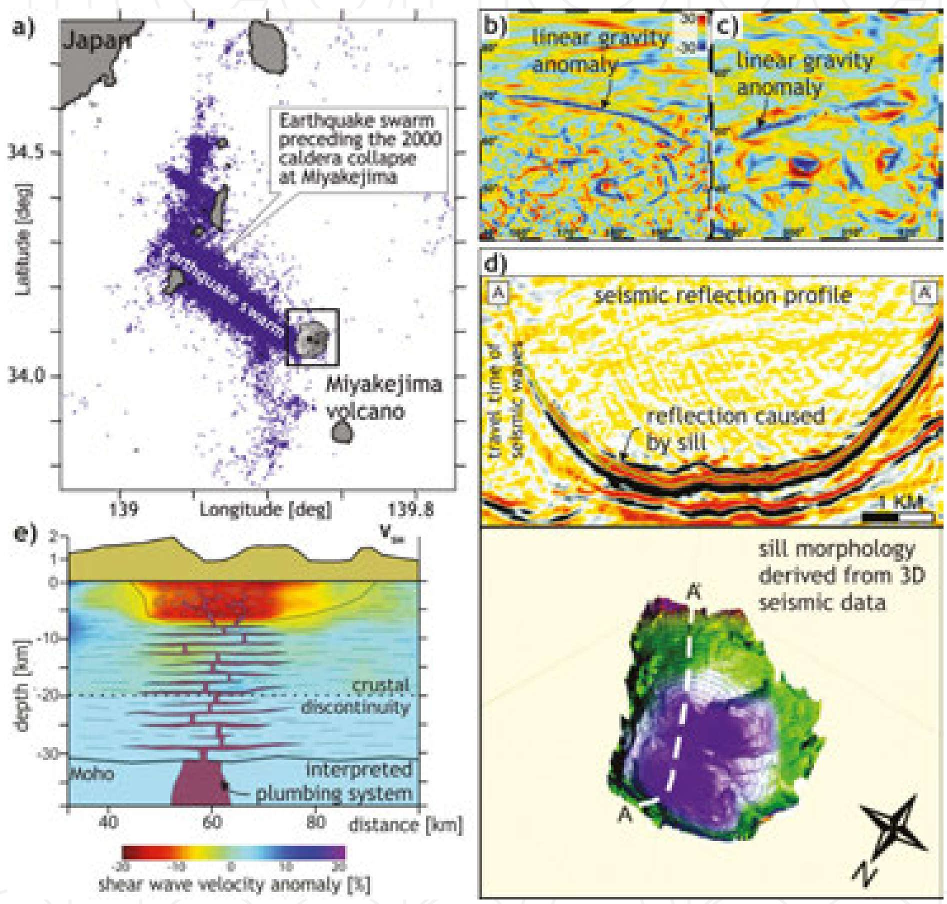

Figure 4. Examples of geophysical studies of volcanic plumbing systems. (a) Seismicity related to the emplacement of a dyke preceding caldera collapse in Miyakejima volcano, Japan, in 2010 [62]; see references therein for source data). (b) and (c) Linear gravity anomalies (marked by black dots) interpreted to be related to dykes on the Moon [59]. (d) Above: Vertical section of a 3D seismic dataset showing the signal related to a sill. Below: 3D seismic image of the same saucer-shaped sill [63]. (e) Volcanic plumbing system of the Toba caldera inferred from seismic tomography [64].

In order to characterise physical properties of different materials in the crust, a wide range of geophysical methods, such as gravimetry, magnetometry, and electrics, are commonly applied to map volcanic plumbing systems and associated hydrothermal systems. These methods detect anomalies in the Earth's gravimetric, magnetic, and electrical resistivity fields. The anomalies are caused by the presence of rock types with properties contrasting to those of the surrounding country rocks, for example, higher or lower density, resistivity etc. Depending on the type and size of target, for example, mapping a granitic intrusion, and the expected depth range of the target, appropriate methods, and acquisition techniques are chosen. Instruments may be mounted on airplanes and satellites or installed in arrays at the Earth's surface. Acquired geophysical data can then be used to map the physical properties of the Earth's crust. Such maps allow locating the extent and map the outline of magmatic intrusions, which is extremely useful for large-scale reconnaissance and mapping in poorly exposed or inaccessible areas, such as moons or other planets (e.g. [59]). The spatial resolution of the data mainly depends on the contrast in physical properties between the target and the country rock. The acquired data on geophysical anomalies can also be used in inversion models that infer the subsurface distribution of a particular physical property by reproducing the pattern and magnitude of the anomaly making simple assumptions about the geology, for example, homogeneity and isotropy of the involved rocks. For instance, the results of inversion models can be applied to determine the subsurface shape and volume of a granitic intrusion (e.g. [60, 61]). The main limitation of geophysical mapping at depth using inversion modelling is that the data are acquired at the Earth's surface (more or less in 2D) is then used to interpret the 3D distribution of physical properties. Moreover, inversion modelling that often produces as very similar solutions in spite of different input parameters. Hence, the number of fitting solutions may be infinite, and thus, model interpretations are often non-unique.

Geophysical methods are also frequently applied to study active volcanoes in order to locate magma storage levels and to infer processes related to magma movement. For instance, microgravimetry monitoring can be applied to detect magma flow into the plumbing system by monitoring changes in the local gravimetric field, a method often combined with geodetic monitoring [65]. In the brittle crust, volcano-tectonic earthquakes that are interpreted to be related to magma movement are studied in the subdiscipline of volcano seismology [66]. Using a network of seismometers, seismicity in active volcanoes can be monitored, for example, to trace propagating sheet intrusions, which gives valuable insight into dyke emplacement mechanisms [67, 68]. The properties of seismic waves (frequencies, wave forms, etc.) can be interpreted to derive information about processes such as the rise of magma in a conduit or the intrusion of a cryptodome [60]. Travel times of seismic waves through the crust beneath a volcano can be used as input parameters for inversion models, a technique called seismic tomography. The seismic velocity structure of a volcano can be used to map subsurface areas with an increased percentage of melt, potentially corresponding to magma reservoirs [69, 51]. However, the detection limit of seismic tomography for magma bodies is on the order of several hundred metres, depending on the seismic array and acquisition conditions on the one hand and the structure of the individual volcano on the other. Therefore, most parts of the volcanic plumbing system, such as average sized dykes and sills, may be undetectable using seismic tomography.

During the last decade, seismic reflection and refraction have been extensively implemented to image volcanic plumbing systems in sedimentary basins [70, 71]. While all geophysical methods described earlier employ passive measurements of natural rock properties, seismic reflection and refraction methods represent active geophysical surveying: acoustic waves are sent into the subsurface and reflected and refracted at interfaces between rocks of contrasting impedance. Thus, the resulting seismic images are a direct echography of subsurface structures and not the result of data inversion. Initially designed for studying the structure of sedimentary basins and hydrocarbon exploration, seismic data proved essential to document the presence of voluminous sill and laccolith complexes in numerous basins worldwide [73, 74]. On seismic images, igneous intrusions are very prominent because of the strong impedance contrast between igneous and sedimentary rocks. The main advantages of seismic data are that (1) they can image the shapes of entire intrusions in three dimension [74, 75], which can potentially constrain magma flow directions [64, 76], and (2) it is possible to constrain the intrusion-scale deformation induced by magma emplacement [77, 78, 83] and intrusion-fault interactions [79]. The main limitations of seismic data are (1) the limited spatial resolution (about 20 to 40 m), (2) the limited possibility to image subvertical features, such as dykes, (3) seismic artefacts that produce interpretable features that do not exist, and (4) the availability of the seismic data, as they are often kept confidential by oil companies.

Geophysical methods are thus powerful tools to study physical properties and signals produced by processes of volcanic plumbing systems. Despite their limitations, these methods are often the only way to derive information about the location and properties of plumbing systems at depth.

3.4. Geodetic studies of volcanic plumbing systems

Volcano observatories monitor active volcanoes with a combination of techniques, including seismic networks, temperature, and gas monitoring, as well as geodetic techniques (www.wo-vo.org; **Figure 5**). Geodetic monitoring of the deformation of the Earth's surface relies mainly on ground-based tiltmeters, GPS networks, and satellite-based Interferometry of Synthetic Aperture Radar (InSAR). A network of GPS stations has to be deployed and maintained in the field and typically delivers daily data for each station. Continuous monitoring can provide surface deformation data with an accuracy of about 1 mm/yr, but the data quality strongly depends on the station network density [80]. On the other hand, InSAR records surface deformation in the line of sight of the satellite at 10–40 days intervals. So, InSAR can reach accuracies of less than 1 cm for a stack of interferograms. Apart from disturbances due to vegetation and glaciation, InSAR allows geodetic monitoring of volcanoes worldwide, irrespective of accessibility [80]. Thanks to InSAR monitoring data, we now know of more than 140 currently deforming volcanoes (http://www.globalvolcanomodel.org).

The corrected and processed surface deformation data are interpreted using geodetic volcano-deformation modelling, which reproduces the pattern and magnitude of the surface signal with analytical models based on fluid and solid mechanics [84]. The results of geodetic models have been used to interpret volcano deformation in many volcanoes worldwide [85–87] and have led to a better understanding of magma movements. Even though surface deformation in volcanoes is not always related to an imminent eruption, geodetic monitoring, and modelling have become standard tools for eruption forecasting [88–90].

Geodetic models are analytical or numerical solutions that comprise three components: A. a deformation source representing the VPS, B. a static process in the deformation source, and C. the model crust bounded by the free surface and characterised by a rheological law. The combination of A, B, and C produces deformation of the model surface, which is compared to the measured surface deformation. As the solution of geodetic models with highly different input parameters can produce very similar results [91, 92], the geodetic modeller is left with an infinite number of possible, non-unique solutions. Non-linear inversion is thus applied to select likely source parameters, to estimate uncertainties, and to compare the goodness-of-fit of different models [93, 94]. When comparing the fit of models, the simplest one, which reproduces the recorded data best, is usually preferred, even though it may be geologically implausible for the studied volcano.

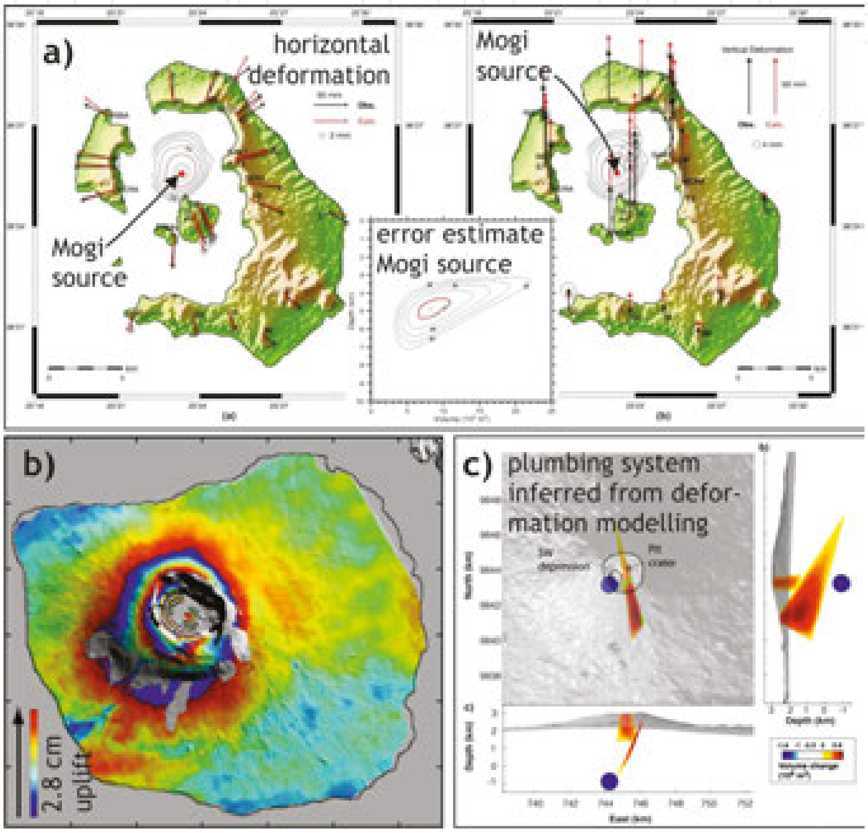

Figure 5. Examples of geodetic studies of volcanic plumbing systems. (a) GPS data (black arrows) and results of Mogi models (red arrows) of ground deformation of Santorini. The Mogi source (red dot) is given with confidence intervals in per cent [81]. (b) Post-eruptive deformation of Fernandina volcano, Galapagos islands, measured with InSAR [82]. (c) Structure of the volcanic plumbing system of Nyamulagira volcano, Congo, inferred from InSAR and stress modelling [83].

Since it is impossible to quantify the uncertainties of geodetic model results on active geological processes that occur in the subsurface, it is important to constrain the models by using model input parameters provided by depth and location of earthquakes related to moving magma [86], earthquake "shadows" around magma reservoirs (see Section 3.3; [69]), or by volcanic eruption volumes and volcanic plume heights [95]. However, these methods miss small- and medium-sized magma chambers, as well as the shape of the plumbing system. Furthermore, geobarometry (see Section 3.2) may indicate the depth and duration of long-term magma storage, but cannot resolve levels of short-time storage [51]. More importantly, however, the lack of collaborative work between different disciplines that study volcanoes has so far prevented a more realistic interpretation of surface deformation in volcanoes. So in practice, deformation source geometries are often arbitrarily chosen without geological validation.

3.5. Laboratory, theoretical, and numerical modelling of volcanic plumbing systems

Since active volcanic plumbing systems are located within the crust and therefore not accessible for direct observations and even the shallowest parts, that is, volcanic vents, are extremely

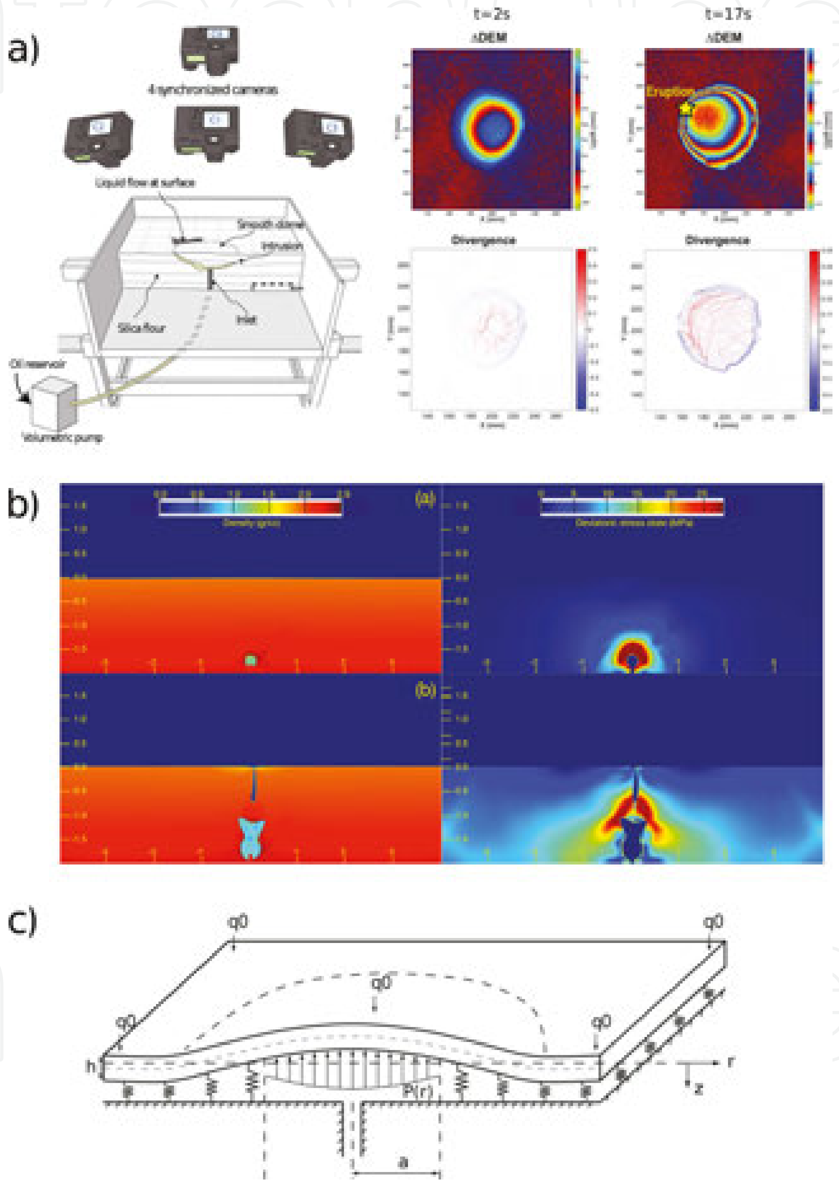

Figure 6. Examples of modelling studies of volcanic plumbing systems. (a) Experimental set-up (left) and characteristic laboratory modelling results (right) of ground deformation induced by shallow magma emplacement [96]. Results are differential DEMs (top row) and divergence maps (bottom row) calculated from horizontal displacement maps at two times of an experiment; positive divergence means dilation (tensile cracks), whereas negative divergence means compression (reverse faulting). (b) Numerical results displaying the evolution of density cross sections (left column) and deviatoric stress cross sections (right column) calculated from 2D finite volume simulations of explosive venting [97]. (c) Set-up and boundary conditions of a theoretical model of flat-lying intrusion of radius a, emplaced at the base of an elastic plate of thickness h and weight q0 [98]. The magma has a heterogeneous pressure $P(r)$.

hazardous to approach, our understanding of the dynamic processes at work in VPS is based on either direct observations of extinct plumbing systems (field geology; see Section 3.1) or indirect observations through geophysics, geodetic surveys, and geochemistry and petrology of volcanic products (see Sections 3.2 to 3.4). However, these approaches are insufficient to identify and quantify the physical parameters and laws that dominantly control the dynamics of VPS.

To overcome these limitations, modelling techniques, such as laboratory, theoretical, and numerical modelling are employed to study processes in volcanic plumbing systems (**Figure 6**). By definition, modelling implies simulating processes in a model system to understand the dynamics of the same processes in nature. However, as the model system is a crude simplification of a part of nature, we cannot expect the model to represent the full complexity of natural processes. The assumptions and simplifications we make when setting up the model, will have a large impact on the model outcome. It is therefore important to keep in mind that models are models, and not nature, and that model results are only as good as the input data. Consequently, modelling of volcanic plumbing systems should always use input data from plumbing systems in nature, for example, field data, and should always be validated against observations in nature.

3.5.1. Laboratory modelling

The aim of laboratory modelling is to simulate processes in volcanic plumbing systems at manageable scales, such as laboratory lengths (sand boxes of a few metres length maximum) and time scales (minutes to days) (**Figure 4a–c**; [20]). In the nineteenth and early twentieth centuries, laboratory models were phenomenological only and used as source of inspiration and/or proof of concepts to demonstrate the existence of a phenomenon [99]. The main limitations of these models were their applicability to geological systems. Laboratory models entered a new era after Hubbert [17] introduced the scaling theory that established scale relationships between laboratory-scale model and geological-scale system. However, these scale relationships address the similarity between the two systems only, that is, they cannot be used to understand the physics behind the modelled processes. Hence, the development of the dimensional analysis concept within the field of physics was a breakthrough for laboratory modelling. Dimensional analysis identifies fundamental physical laws, so-called scaling laws, that are simple relationships between dimensionless parameters, that is, their validity is scale independent ([100] and references therein). Combining dimensional analysis and similarity principles to laboratory models allow the modeller to unravel the fundamental physical laws and apply them to geological-scale volcanic plumbing systems [20].

Successful implementation of laboratory models requires the use of model materials with relevant properties. Classic rock analogues are gels [101, 102] and loose sand [103, 104] to simulate elastic rocks and cohesion-less Coulomb (i.e. frictional) rocks, respectively, which are two end-member behaviours of natural rocks. Recently, new materials of more complex rheology have been successfully used [105, 106]. Cohesive granular materials, some of which have variable cohesion, account for the complex elastoplastic properties of the brittle upper crust, and can simulate both mode I (tensile) and mode II (shear) fracturing [107]. Gels offer the possibility to study the viscoelastic properties of the Earth's crust [108– 110]. On the other hand, many different fluids of diverse rheology and viscosity have been used as magma analogues [20]. Most noticeable is the implementation of two-phase fluids to model the dynamics of magma-bubble suspensions [111, 112]. These materials offer the possibility to model the natural complexity of geological systems, and hence, the physics of the complex processes in volcanic plumbing systems is studied.

Another recent enhancement of laboratory models has been the implementation of various monitoring methods that allow for more quantitative data acquisition and analysis [113]. The most commonly used methods are Particle Image Velocimetry (PIV) and Digital Image Correlation (DIC) [62, 114, 115] and stereo-photogrammetry [96] to monitor deformation of surfaces, as well as X-ray scanners to monitor *in situ* model interiors [116, 117]. The resulting quantitative data have become essential for (i) constraining the physical laws governing the modelled processes and (ii) integrating laboratory results with quantitative geological, geophysical and geodetic data.

The main limitations of laboratory models to be considered include the scale gap between the laboratory and geological systems, which is often critical and hard to fully constrain. The full characterization of model materials is not straightforward, even though it is essential, and requires a solid fundamental mechanics background. For example, cohesive and cohesion-less granular materials exhibit elastic properties that are difficult to measure, though they are crucial for the dynamics of the brittle crust [118, 119]. Another challenge is connected to recording the modelled processes, which often requires advanced techniques, such as laser or X-ray scanning, which are very costly and heavy to handle. Moreover, stress fields in granular material experiments cannot be measured, although stress distribution is a key factor on the dynamics and evolution of VPS. Finally, first-order assumptions need to be made due to technical limitations of model systems, neglecting for instance thermal effects [120] and chemical evolution of magmas.

3.5.2. Theoretical modelling

In order to assess first-order scaling laws governing a process in volcanic plumbing systems, theoretical (or analytical) models are employed. Theoretical models solve analytically or semianalytically the mathematical equations governing the studied processes (**Figure 4d**). During the mathematical derivations, the first-order scaling parameters commonly appear spontaneously [98, 121, 122], such that the first-order effect of the key physical parameters is obvious, and it is possible to identify whether distinct physical behaviours can be expected. Pioneering theoretical models of hydraulic fractures [123, 124], for example, are the foundation for most subsequent models of dyke or laccolith emplacement.

Although theoretical models are powerful, they require an advanced level of mathematical skill, which is often beyond the training level of most geoscientists. Moreover, theoretical models exhibit limitations, such that the solution of the equations requires a large number of simplifying assumptions. As a consequence, many geoscientists are not aware of the assumptions behind the mathematical models and extrapolate the model results beyond their domain of validity. Furthermore, geoscientists often accept the assumptions underlying the theoretical models as rules, such that the assumptions are rarely questioned, in spite of contradicting evidence from nature. For example, it is commonly assumed that dykes and sills are hydraulic fractures emplaced in purely elastic host rocks, although clear field, geophysical, and laboratory evidence of first-order inelastic deformation accommodating their emplacement are frequently observed.

3.5.3. Numerical modelling

Numerical modelling uses mathematical equations to simulate a simple process or a combination of several processes (**Figure 4e**). Using numerical codes and software, which have often been developed for materials science applications, the studied system is subdivided into subsystems, so-called elements, and the equations solved for each element. Hence, numerical models can overcome some of the main limitations of theoretical models by accounting for boundaries of complex shapes [125], complex heterogeneities, etc. The models can take into account material properties, temperatures and pressures and calculate stresses and strains, as well as changes in temperature, pressure, and material properties. Furthermore, numerical models can account for static [86, 126], quasistatic, and transient processes [127, 128]. Therefore, in a transient model, it is possible to calculate at each time step, the stress field [129], flow field [130], and/or temperature field [131]. This represents a major advantage with respect to laboratory models, in which the material properties and processes within the model are challenging to measure and monitor. Another advantage is that the scales of numerical models can be directly set as the scale of geological systems. As computational power is the main constraint on how complex a numerical model may be, it is easy to systematically vary model parameters, such as the material properties, a major advantage compared to laboratory modelling.

There are two main types of numerical models with fundamentally different approaches, continuum models and discrete models. Continuum models solve the fundamental equations of continuum mechanics, such as Stokes and Navier-Stokes equations for fluid flow, Hook's law for elastic deformation, the heat equation calculating heat diffusion and/or advection, and Darcy's law for porous flow. Various solving methods exist, such as finite difference [132], finite element (e.g. [128]), and finite volume [97]. In volcanic plumbing system research, continuum models are commonly used to model the elastic deformation induced by magmatic intrusions [42, 86, 133], magma flow within intrusions [125], thermal impacts of intrusions on their host rock [131, 134], thermal convection within magma reservoirs [130], and recently magma emplacement [128, 132]. The main limitation of continuum models is that they cannot simulate the formation of new discontinuities, such as fractures or dykes, which is why the geometry of discontinuities has to be prescribed [42].

Discrete models calculate the behaviour of a pack of particles that interact with each other. Some main methods are discrete element models (DEM) and Lattice Boltzman (LBM). The particle interactions are represented by bounds with elastic, friction, or fluid-like properties and strengths [135]. Discrete models are very valuable to simulate processes that create discontinuities, such as fractures, and they appear very suitable to simulate caldera collapse [127], dyke, sill, and laccolith emplacement [129, 136]. The main limitation of discrete models is to link the particle-scale interactions (e.g. bound stiffness, bound strength) with the bulk properties of the particle packing (Young's modulus, cohesion, internal friction), requiring heavy systematic calibration before running the models and interpreting the results.

4. Challenge: integrating the methods

Since our training and level of experience fundamentally influence how we interpret geological problems [137], different studies of volcanic plumbing systems that employ methods of different disciplines often lead to contradictory conclusions. For instance, shallow magma storage beneath Katla volcano has been suggested based on seismic and geodetic data [138, 139], whereas petrological studies so far found evidence for lower- to mid-crustal storage only [140]. Such contrasting results may lead to fundamentally different interpretations when it comes to volcanic risk and hazard assessment and may therefore have unforeseeable consequences (cf. [58]). However, these contrasting results may be due to the limitations of individual methods that commonly assess a fraction of the complex magmatic dynamics only, a discrepancy that is hardly possible to assess for decision makers.

The disciplinary boundaries in plumbing system research in part reflect the historical development of the Earth sciences in general (see Section 2). During the twentieth century, each of the disciplines involved in the study of magma transport and storage has become more specialised, and new disciplines, such as volcano geodesy, have emerged. Methods have become more and more sophisticated, revealing the complexity of individual, and the interplay between, physical and chemical processes at scales ranging from the size of the crystal lattice to the thickness of the lithosphere. While specialisation and methodological progress naturally continue, the true challenge of the twenty-first century is to overcome the boundaries of our disciplines in order to truly assess the complexity of volcanic plumbing system dynamics.

There are three key components required to foster multidisciplinary research in general, and VPS research in particular: communication, information, and education. The methodological specialisation of each discipline has been naturally accompanied by the development and evolution of specific terms, and in most cases even jargon, that are used within individual disciplines, but might not be accessible to researchers outside of the particular discipline. For instance, while structural geologists may refer to a magma body of a certain size as "pluton", the same intrusion may be a "magma reservoir" to igneous petrologists, a "shadow in s-wave attenuation" to geophysicists, and a "deformation source" to geodesists. On the other hand, different disciplines may use the same term but with different connotation. In order to overcome disciplinary boundaries, we need to be able to understand each other, which is preferentially achieved by developing a common language and avoiding jargon. In addition, it is key to learn to communicate one's research to a broad audience, for example, by explaining the essential message of a certain diagram or equation in terms of the research question or by summarising research results in the end of a publication in a way that is generally understandable.

	Field studies	**Petrology**	**Geophysics**	**Geodesy**	**Modelling**
Key questions	*How is magma transported, stored & erupted? Is there an interaction with the host rock?*	*How does magma form and evolve? When did the magma form? What triggers eruptions?*	*Where does the signal come from? What does it mean? Is the signal magmatic?*	*What does the deformation signal mean? Is the signal magmatic?*	*How does the magmatic plumbing system work? Are there general laws we can apply?*
Contribution from [below] towards [above]					
Field studies		Relative ages; structure; context & correlation; mechanical control	Lithology; types of structures; resolution	Shape & evolution of sources; complexity; response of rocks to deformation	Interpretation of kinematics; structural relationships; geometry; mechanics; properties
Petrology	Absolute ages; origin of magma; source evolution; eruption types; chemostratigraphy		Composition of samples; depths & rates; thermal evolution; rock properties	Depths of storage; time scales; sources	Time scales; composition; feedback
Geophysics	Depths & sizes; 4D imaging at depth	Rates; depths & sizes; 3D to 4D imaging at depth		3D to 4D imaging at depth; rock properties & geometries; rates	Rock properties; rates of processes
Geodesy	3D crustal structure; depths & sizes; rates	Rates; depths & sizes; temperature; density	Rates		Response signal of rocks due to processes
Modelling	Feedback on mechanisms & processes; interpretations of structures	Conceptual context; quantify conditions of magma evolution	Mechanisms & processes; state of stress	Mechanisms & processes	

Table 1. Overview of the main disciplines involved in studying volcanic plumbing systems, their main foci and the contribution each one of them can make to the other disciplines.

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Another requirement to overcome disciplinary boundaries is to inform researchers from other disciplines about the capabilities and limitations of our own approaches, a process that requires clear communication. At the same time, we need to learn how other approaches can be used to complement our own methods. **Table 1** provides an overview of how approaches from each of the disciplines described earlier (Section 3) can complement research in other disciplines. The key questions and strengths of any of the disciplines can provide complementary data for research in other disciplines. For instance, quantitative constraints on the dimensions of sheet intrusions derived from field work in eroded volcanic systems [32, 141] can be used as input parameters for geodetic modelling of volcano deformation. Geobarometric calculations of the crystallisation depth of crystals in eruptive products of a volcano can be combined with seismic tomography to constrain the depth of magma storage [51]. 3D seismic imaging of intrusions in sedimentary basins can complement field studies on the shape and emplacement of sills [79, 129]. Geodetic monitoring data may help to quantify the amount of magma drained from the volcanic plumbing system during dyke intrusion [142]. Modelling of the emplacement of sheet intrusions can reveal the parameters that control what type of intrusion forms and why different sheet intrusion types are found in the same volcanic plumbing system [143]. These examples highlight only some of the benefits of combining different approaches.

Finally, we need to educate future generations of researchers to be open-minded and aware of the potential of other methods and to be able to communicate their research to a broad audience and collaborate beyond disciplinary boundaries. Multidisciplinary conferences, workshops, and research meetings should become common practice, as should multidisciplinary research projects and teams.

It is up to each one of us to try and understand the potential of other disciplines' methods, to communicate our research so that we can be understood beyond our own disciplines, and to educate our students to be open-minded and have a broad overview of the approaches in volcanic plumbing system research. Although this development may at first glance look like an about-face from the trend of specialisation in our disciplines, in reality, it implies the chance for a more thorough characterisation of the complexity of volcanic plumbing systems.

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