Bulletin of Volcanology (2022) 84: 59
https://doi.org/10.1007/s00445-022-01564-6

PERSPECTIVES

Developments in the study of volcanic and igneous plumbing systems: outstanding problems and new opportunities

Steffi Burchardt[1,2] · Catherine J. Annen[3] · Janine L. Kavanagh[4] · Suraya Hilmi Hazim[5]

Received: 15 July 2021 / Accepted: 8 April 2022 / Published online: 18 May 2022

Abstract

Prior to and during eruptions, magma is stored and transported within volcanic and igneous plumbing systems (VIPS) that comprise a network of magma reservoirs and sheet intrusions. The study of these VIPS requires the combination of knowledge from the fields of igneous petrology, geochemistry, thermodynamic modelling, structural geology, volcano geodesy, and geophysics, which express the physical, chemical, and thermal complexity of the processes involved, and how these processes change spatially and temporally. In this contribution, we review the development of the discipline of plumbing system studies in the past two decades considering three angles: (1) the conceptual models of VIPS and paradigm changes, (2) methodological advances, and (3) the diversity of the scientific community involved in VIPS research. We also discuss future opportunities and challenges related to these three topics.

Keywords Eruptions · Magma · Volcanic and igneous plumbing systems · Scientific community

Introduction

Volcanic unrest recorded at the Earth's surface prior to and during eruptions is usually caused by sub-surface processes within the volcanic and igneous plumbing system (VIPS), such as magma transport within sheet intrusions and the establishment and evolution of magma reservoirs that feed those sheet intrusions (e.g. Biggs and Pritchard 2017; Sigmundsson et al. 2018; Sparks et al. 2019). Traditionally, VIPS have been studied in different sub-disciplines of the Earth sciences in parallel (Fig. 1; Burchardt 2018). Examples include as follows:

a. the study of the composition of igneous rocks and minerals to reconstruct the conditions in magma reservoirs (e.g. Sparks et al. 1977; Putirka 2008; Bindeman 2008),
b. mapping of dyke swarms to shed light on the syn-emplacement stress conditions (e.g. Ernst et al. 1995; Hoek and Seitz 1995; Srivastava et al. 2019),
c. the use of seismicity beneath active volcanoes to map zones of magma storage (e.g. Scarpa and Gasparini 1996; McNutt 2005; Lees 2007), and
d. location of seismicity related to magma transport (e.g. Ebinger et al. 2008; Bell and Kilburn 2012; White et al. 2019).

Early research on plumbing systems was often restricted to single disciplines, such as the examples mentioned above. However, since the 1980s, volcanic eruptions, such as those at Mount St Helens, Pinatubo, and Montserrat, have shown the importance of multidisciplinary work to better understand the role of shallow reservoirs and conduits controlling or influencing eruption style (e.g. Eichelberger and Hayes 1982; Cashman 1988; Voight et al.

Editorial responsibility: K.V. Cashman

This paper constitutes part of a topical collection:

Looking Backwards and Forwards in Volcanology: A Collection of Perspectives on the Trajectory of a Science

✉ Steffi Burchardt
steffi.burchardt@geo.uu.se

1 Department of Earth Sciences, Uppsala University, Uppsala, Sweden

2 Centre of Natural Hazards and Disaster Science, Uppsala/Stockholm/Karlstad, Sweden

3 Institute of Geophysics of the Czech Academy of Sciences, Prague 4, Czechia

4 School of Environmental Sciences, University of Liverpool, L69 3GP, Liverpool, UK

5 Geology Programme, The National University of Malaysia, 43600 Bangi, Selangor, Malaysia

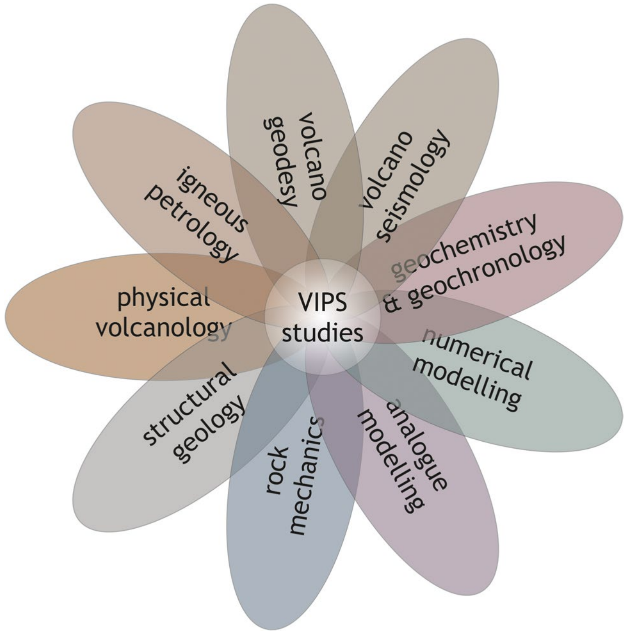

Fig. 1 Venn diagram showing the relationship between diverse research fields within Earth sciences and their overlap to contribute to the study of VIPS. The multidisciplinary approach at the centre of the diagram has led to the greatest scientific advance in understanding VIPS

2014). It is through this multidisciplinary approach that the strongest advancements in VIPS studies have continued to be made through the second decade of the twenty-first century (Figure 1).

Understanding magma transport and storage in VIPS is fundamental in estimating volcanic risk, as processes within the VIPS largely control whether an eruption will occur, what type of eruption it will be, and for how long it will last. Other areas where VIPS are of major significance are as follows:

1. crustal growth at plate boundaries and in intraplate settings (e.g. Christensen and Salisbury 1975; Brown 1994; Marinoni 2001),
2. the release of climate-active volatiles during the formation of Large Igneous Provinces (LIPs; e.g. (Aarnes et al. 2010; Svensen et al. 2018; Ernst et al. 2021),
3. heat flow, hydrocarbon maturation, and structural control on hydrocarbon reservoirs in sedimentary basins (Polteau et al. 2008; Senger et al. 2017; Spacapan et al. 2018),
4. the formation of economic deposits of ores and diamonds (e.g. Ganino et al. 2008; Sillitoe 2010; Elliott et al. 2018; Russell et al. 2019), and
5. the formation of geothermal resources (e.g. Sibbett 1988; Boyce et al. 2003; Stimac et al. 2015).

Hence, there are many reasons why VIPS research is both essential and relevant for research and society today.

VIPS studies are thus a dynamic and growing field that is, today, more integrated across the various sub-disciplines of volcanology. In the following assessment, we describe the developments that led to the integration of VIPS studies and the current state-of-the-art in VIPS research in terms of both conceptual understanding and methodological advances. We outline some general trends and explore how the methodological development is improving understanding of magma transport and storage, especially by exploiting opportunities and revealing new challenges. Moreover, we discuss how the scientific community involved in VIPS has evolved. We finally highlight open questions for future research and the need to include a diverse group of people if VIPS research is to continue to evolve in such a positive direction.

Paradigm shifts and state of the art in VIPS studies

Prior to the twenty-first century, several different conceptual models of igneous plumbing system were developed (Figure 2a), some of which have now been abandoned. Prior to 2000, the most prominent concept was that the large amount of granitoid rocks exposed at the Earth's surface originated from crystallisation of huge, fully molten, and long-lived magma chambers. How these magma chambers were emplaced in the crust had been a long-standing dilemma throughout the nineteenth and twentieth centuries (termed 'the space problem'; e.g. Bowen 1948; Read 1957; Hutton 1996). However, methodological advances in the fields of geochronology and geochemistry in the early 2000s demonstrated that granitoid plutons were in fact assembled by the amalgamation of multiple small magma batches over millions of years (Coleman et al. 2004; de Saint Blanquat et al. 2011). This insight agreed with seismic tomography studies of the crust beneath active volcanoes that found the presence of only a few percent of melt (Lees 2007). Diffusion chronometry in crystals from volcanic products also revealed magma storage at rather 'cold', i.e. below magma liquidus temperature, conditions for most of the residence time of erupted crystals (Cooper and Kent 2014).

A new paradigm thus began to emerge that encompassed magma storage in a plumbing system mainly composed of an uneruptible, crystal-dominated 'mush', where melt exists between crystals or in small pockets (Figure 2b). The concept is not completely new (Marsh 2004; Bachmann and Bergantz 2004), but has gained recent momentum as it elegantly explains the diversity of crystal ages within erupted materials and facilitates the fast assembly of mostly molten, but ephemeral, magma reservoirs (Cashman et al. 2017). Thermodynamic modelling

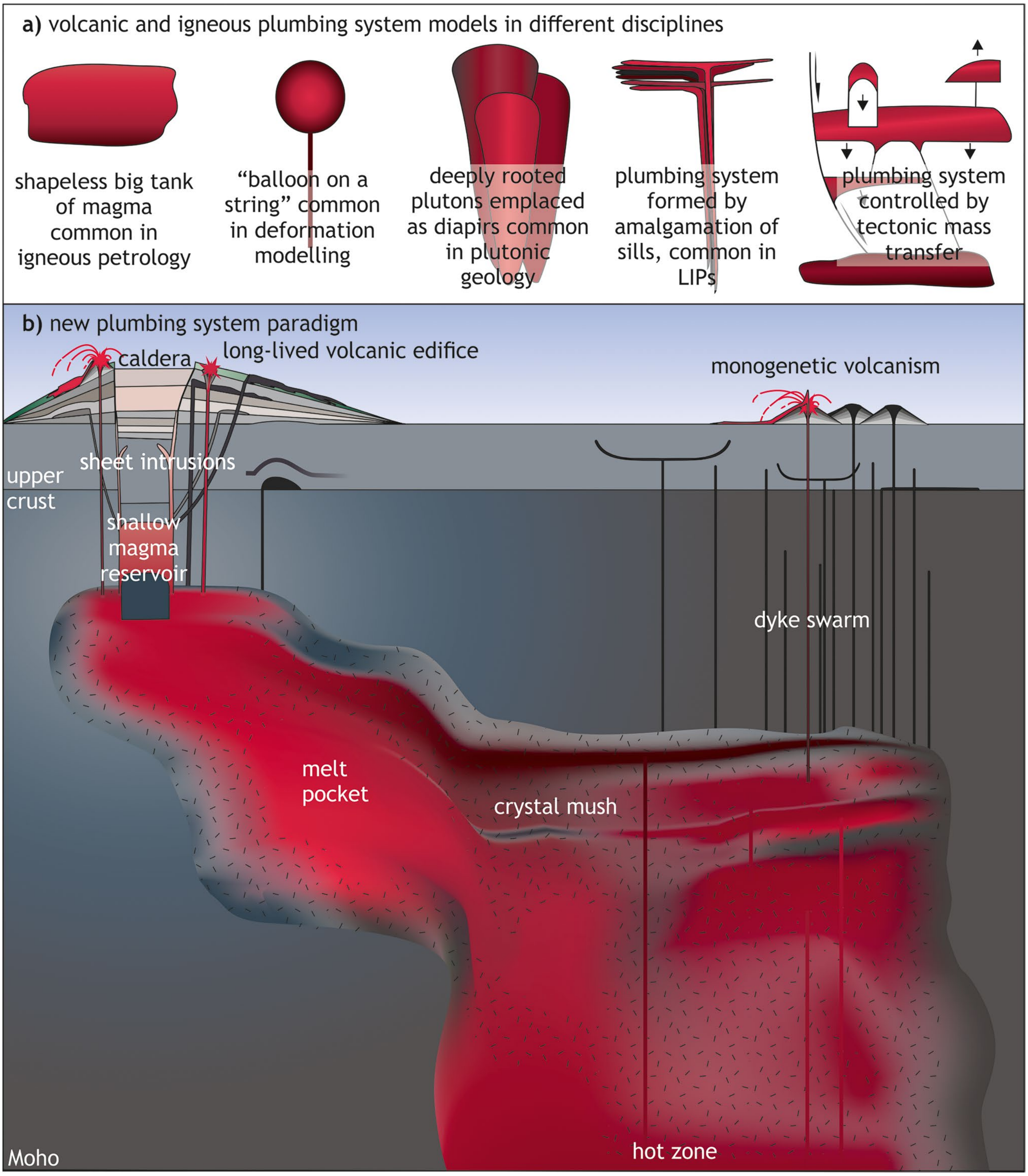

Fig. 2 Schematic illustrations of **a)** the range of different traditional VIPS models in different disciplines (Burchardt 2018) and **b)** how aspects of these now are reconciled within the new 'mush' plumbing system paradigm

of the 'mush plumbing system' (e.g. Petford et al. 2000; Annen et al. 2006; Bachmann and Huber 2016; Jackson et al. 2018; Huber et al. 2019; Annen and Burgisser 2020) has also shown how the system evolves thermally through the addition of small magma batches, how the magma composition can evolve, and how shallow magma storage and magma degassing can contribute to the eruptive potential of volcanoes. However, thermodynamic modelling also shows that mush extent and longevity are limited by the amount of heat available in the crust (Glazner 2021).

Current research addresses the properties of crystal mush, its generation, and how magma is remobilised within the mush before large eruptions (e.g. Spera and Bohrson 2018; Wieser et al. 2020; Humphreys et al. 2021). Moreover, the mush paradigm will need to reconcile evidence which supports the existence of long-lived and largely molten magma bodies in the geological record (e.g. Barboni et al. 2016; Kruger and Latypov 2020; Rout et al. 2021), to explain the formation of the thermal anomaly required for the generation and persistence of large volumes of mush in the upper crust, and to acknowledge that the lack of high melt fraction reservoirs recovered by seismic tomography may be due in part to a problem of spatial resolution (Paulatto et al. 2019).

Another major conceptual advance in the field of VIPS studies focuses on the transport of magma through sheet-like (dyke and sill) and cylindrical (conduit) pathways. In the last two decades, the insight that magma transport is most efficient through magmatic sheet intrusions has been confirmed by field-based monitoring of seismicity related to propagating intrusions and remote observation of surface deformation patterns (e.g. Ebinger et al. 2008; Bell and Kilburn 2012; Sigmundsson et al. 2014). Even within the lower crust, magma transport is believed to be possible through dyking resulting from self-organisation and convergence of thin magma-filled veins (Cruden and Weinberg 2018).

A broad array of methods, such as field studies in areas with exposed, solidified sheet intrusions, high-resolution 3D seismic surveys of sedimentary basins, and active plumbing systems at mid-ocean ridges, and numerical and laboratory models have all highlighted:

1. the variety of sheet intrusion geometries, including sub-vertical dykes, inclined cone-sheets, and concordant sills (e.g. Galland et al. 2018; Kavanagh 2018; Burchardt et al. 2018),
2. their internal complexity (e.g. Magee et al. 2016; Schmiedel et al. 2021; Köpping et al. 2022),
3. the abundance of these sheets in the plumbing systems (Walker 1992; Walker and Eyre 1995; Tibaldi and Pasquarè 2008), and
4. their interaction with host rock structures and lithologies (e.g. Krumbholz et al. 2014; Spacapan et al. 2017; Norcliffe et al. 2021).

Within this framework, ongoing research on sheet intrusions thus addresses the relationship between the dynamic emplacement and associated volcanic unrest signals, as well as the interplay between tectonics and the magma/host-rock properties, and how understanding of the macro- and micro-scale temporal and spatial processes can be reconciled in such meso-scale structures (cf., Galland et al. 2018; Kavanagh 2018; Burchardt et al. 2018).

Currently, knowledge on VIPS processes based on field studies (e.g. Holness and Humphreys 2003; Stephens et al. 2017; Spera and Bohrson 2018; Mattsson et al. 2018; Martin et al. 2019) and modelling (e.g. Gudmundsson et al. 2016; Guldstrand et al. 2018; Drymoni et al. 2020) is integrated into the interpretation of volcanic unrest and eruptive activity. In the past, volcano deformation modelling has successfully reproduced the signals recorded by monitoring networks (Neal et al. 2019). However, the modelled solutions were generally non-unique and not always geologically plausible (Bertelsen et al. 2021). In the next decade, the integration of VIPS research on, e.g., the mechanisms of dyke propagation and deformation associated with the establishment of magma bodies into unrest modelling will contribute to more realistic interpretations of volcano monitoring data, which will lead to better risk management and hazard mitigation.

Methodological developments in VIPS studies

Since the 1950s, a major trend in all fields of the Earth sciences has been the transition from a qualitative, descriptive science towards quantification and accuracy. This began when analogue and numerical models appropriate for magmatic and volcanic systems began to emerge (e.g. Morton et al. 1956; King et al. 1957; Kavanagh et al. 2018). Studies of industrial plumes were applied to model volcanic plumes (Morton et al. 1956), and hydraulic fractures in boreholes were developed as analogues for dyke and sill emplacement (King et al. 1957). Magma chamber processes were then explored in several pioneering analogue experiment studies in the 1980s and combined with insights from numerical models and igneous petrology (Kavanagh et al. 2018); his was a key moment of driving forwards the discipline (e.g. Huppert and Turner 1981; Huppert and Sparks 1981; Turner et al. 1983; Huppert et al. 1983). These models were very effective, and are still held as formative studies in VIPS because they involved multidisciplinary collaborations between mathematicians, fluid dynamicists, engineers, volcanologists, petrologists, and geochemists. The current developments in analogue modelling in volcanology are discussed by Poppe et al. (2022, in press).

The development of multidisciplinary quantitative studies is aided today by rapidly increasing computational power and increasing precision of analytical techniques. Access to commercial software, often developed for industrial purposes, such as the petroleum industry, engineering, or material science, allows VIPS research to benefit from the improvements in these, often better-funded, fields. At the same time, open access to numerical codes designed by researchers allows everyone to apply codes developed for specific Earth science problems. In addition, broad access to satellite images has opened up new opportunities ranging from fieldwork planning and detailed remote sensing to near real-time deformation monitoring at active volcanic systems (Burchardt and Galland 2016). Even in the field, the use of low-cost unmanned aerial vehicles (drones) allows access to previously inaccessible localities, as well as the quantitative study of structural features on virtual outcrops created through photogrammetry. This advance allows for studying aspects of plumbing systems, such as the growth of (crypto)domes, the quantification of magma-induced deformation, and the detailed study of intrusion geometries (e.g. Belousov et al. 2005; Thiele et al. 2021; Rhodes et al. 2021).

Although these and other methodological developments have provided data and models of previously unachievable precision, new challenges have emerged in how to handle, store, and share these data (cf. Science Europe, 2021). Another challenge is connected to the ease of access to tools such as numerical modelling software and bench-top analogue experiments. It is now perhaps easy to create a seemingly correct model output even if one lacks understanding of the physics behind the modelling process and how appropriate the model output is to the natural phenomena. This dilemma stresses the need for ground truthing of modelling output by means of empirical and experimental studies. In addition, it leads us to look at how the research community involved in VIPS studies has developed in the last two decades.

Past, present, and future of the VIPS research community

At the beginning of the twenty-first century, VIPS were still studied as part of separate and different disciplines within the Earth Sciences, most not necessarily linked to volcanology at all (Burchardt 2018). For instance, igneous intrusions were studied by both structural geologists and igneous petrologists, and the results were published in separate specialised journals for structural geology and igneous petrology without linking to each other. On the other hand, books were published in volcanology that barely mentioned the plumbing systems which feed the eruptive products.

However, a transition towards a more integrated and multidisciplinary approach to studying VIPS has become more common in the last decade (e.g. Voight and Sparks 2010; Sigmundsson et al. 2010, 2014; Pritchard et al. 2018; Neal et al. 2019). In our opinion, this transition has been fuelled by three factors:

1. volcanic eruptions that have inspired the formation of multi-disciplinary consortia, such as the eruption of Eyjafjallajökull in 2010 that spurred a number of large-scale projects, such as FutureVolc, and the 2021 eruption of La Palma, Canary Islands.
2. scientific conference sessions, symposia, and workshops with a clear, multidisciplinary scope, such as at the EGU, AGU, and IAVCEI general assemblies, and
3. the formation of the IAVCEI Commission on Volcanic and Igneous Plumbing Systems (https://vipscommission.org/).

Magmatic activity in general, and volcanic activity in particular, involves complex physical and chemical processes. These unfold over time and length scales that span many orders of magnitude from seconds to millions of years and from nm to hundreds of km. Grasping even part of this complexity thus demands the combination of multiple methods capable of addressing this huge range in temporal and spatial scale. The different strengths of each approach partly overcome their weaknesses such that the whole is greater than the sum of its parts (Burchardt and Galland 2016; Edmonds et al. 2019). This can best be achieved in multidisciplinary consortia where experts from different fields work together with a common goal.

An immediate challenge for such consortia, as well as in multidisciplinary conference sessions and workshops, is the establishment of a common language. The history of Earth sciences has in the past been characterised by increasing specialisation, which fostered the development of specialised terminology and scientific jargon in different fields. An example is the diverse use of the term ‘magma chamber’ (cf. Lees 2007; Glazner et al. 2016; Burchardt 2018): while for instance petrologists may picture shapeless reservoirs hosting the chemically evolving melt, crystals, and volatiles they call magma, the structural geologists traditionally envision intrusions of characteristic shapes reflecting specific emplacement mechanisms of the passively emplaced fluid they call magma. Geophysicists on the other hand detect magma chambers as sub-surface anomalies of seismic wave speeds corresponding to hot rocks with some percentage of melt. Shaping an effective multidisciplinary research community that studies the complexities of VIPS thus needs to also focus on sharing knowledge through effective communication.

Scientific jargon is exclusive, and so is a lack of diversity among scientists regarding both disciplines and personal attributes. An inclusive and diverse scientific community will combine the strengths of different methods, build on knowledge of the past, and include new ideas to improve the understanding of magma transport and storage (Figure 3). This is why the IAVCEI Commission on VIPS, founded in 2016, is actively working to provide a platform with a global

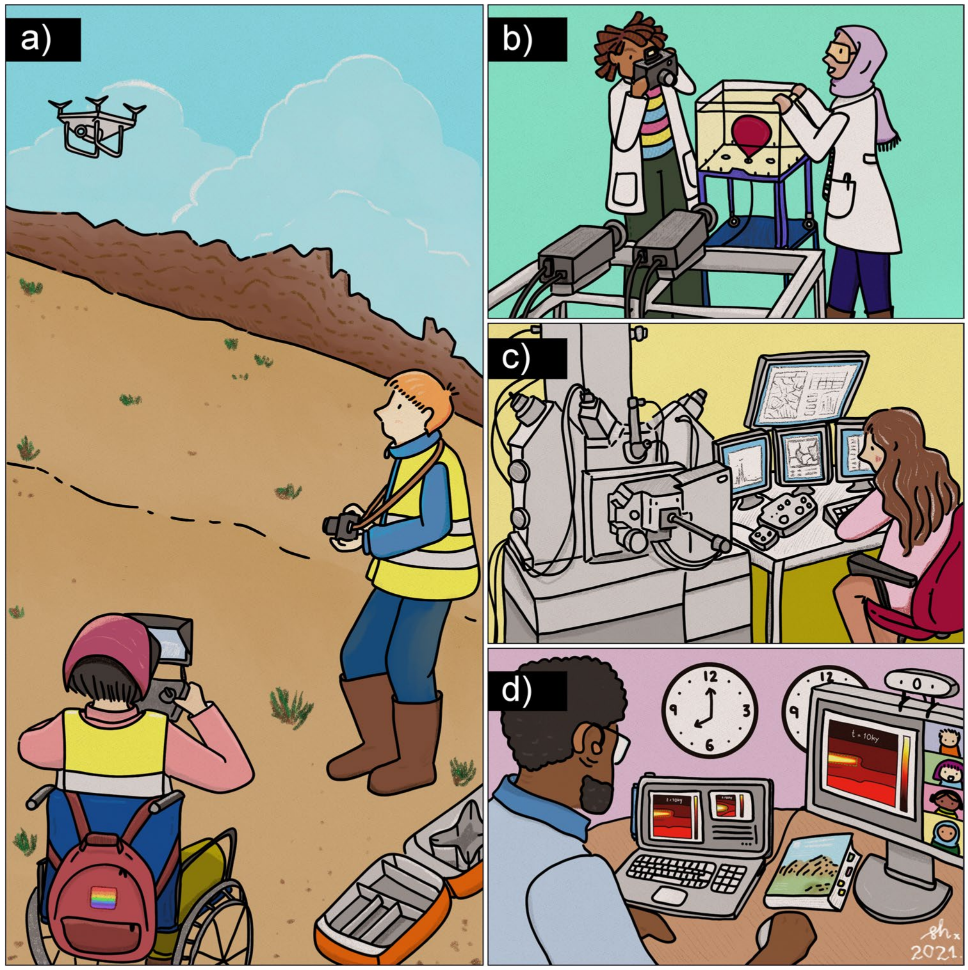

Fig. 3 Our vision of a diverse and inclusive research community studying VIPS using many different methods: **a** expert field geologists, **b** expert analogue (experimental) modellers, **c** expert petrologists and geochemists, and **d** expert numerical modellers.

reach for multidisciplinary dialogue, collaboration, and outreach, including an ambitious plan for improving equality, diversity, and inclusivity (see www.VIPScommission.org; Kavanagh et al. 2022, this volume).

As in other branches of Earth Science, there is a tendency to extend the conclusions drawn from one case study into general models and ignore the diversity and complexity of the processes involved. Collaborative efforts and multidisciplinarity are the best ways to avoid this pitfall. The next decade of research on VIPS thus needs:

1. researchers that are experts in using their methods, but who are able to communicate beyond their own field,
2. generalists with an overview of different methods, thereby allowing identification of new connections or opportunities,
3. working environments that allow full, open, and respectful collaboration between Earth scientists and experts from other fields,
4. constructive communication between researchers working in the field, in laboratories, as well as modellers, and observatory personnel, and
5. above all, our discipline needs to support and nurture a diverse group of students with a solid education in the Earth sciences and a broad outlook so that they dare to question the state-of-the-art assumptions of our field and create new knowledge.

Outlook

The study of magma transport and storage in VIPS has, in the last two decades, emerged as its own sub-discipline within volcanology, from a history of evolution that was dispersed across separate fields. Our vision is of a science that embraces the diversity and complexity of volcanic and igneous systems, while focusing on defining the general laws that underpin the functioning of VIPS. One of the big challenges that researchers will have to address in the upcoming decade is the link between VIPS dynamics and eruption dynamics in order to improve our ability to forecast eruptions and to use VIPS knowledge to reduce the hazards and negative societal impacts of volcanism. We hope that the next decade thus will see an even closer integration of different methods with the aim of better understanding the processes of magma transport and storage in the Earth's crust. This integration will happen in a more inclusive and diverse scientific community that will unravel some of the remaining big questions on VIPS and come up with many new questions to address.

Funding Open access funding provided by Uppsala University. JK acknowledges a UKRI Future Leaders Fellowship (MR/S035141/1). CA was supported by a grant IXXI from the Institut rhônalpin des systèmes complexes. SB acknowledges a Wallenberg Academy Fellowship by the Knut and Alice Wallenberg Foundation (KAW 2017.0153).

References

Aarnes I, Svensen H, Connolly JAD, Podladchikov YY (2010) How contact metamorphism can trigger global climate changes: modeling gas generation around igneous sills in sedimentary basins. Geochim Cosmochim Acta 74:7179–7195. https://doi.org/10.1016/J.GCA.2010.09.011

Annen C, Blundy JD, Sparks RSJ (2006) The sources of granitic melt in Deep Hot Zones. Trans R Soc Edinb Earth Sci 97:297–309. https://doi.org/10.1017/S0263593300001462

Annen C, Burgisser A (2020) Modeling water exsolution from a growing and solidifying felsic magma body. Lithos 105799. https://doi.org/10.1016/j.lithos.2020.105799

Bachmann O, Bergantz GW (2004) On the origin of crystal-poor rhyolites: extracted from batholithic crystal mushes. J Petrol 45:1565–1582. https://doi.org/10.1093/PETROLOGY/EGH019

Bachmann O, Huber C (2016) Silicic magma reservoirs in the Earth's crust. Am Mineral 101:2377–2404

Barboni M, Boehnke P, Schmitt AK et al (2016) Warm storage for arc magmas. Proc Natl Acad Sci U S A 113:13959–13964. https://doi.org/10.1073/PNAS.1616129113/-/DCSUPPLEMENTAL

Bell AF, Kilburn CRJ (2012) Precursors to dyke-fed eruptions at basaltic volcanoes: Insights from patterns of volcano-tectonic seismicity at Kilauea volcano, Hawaii. Bull Volcanol 74:325–339. https://doi.org/10.1007/s00445-011-0519-3

Belousov A, Walter TR, Troll VR (2005) Large-scale failures on domes and stratocones situated on caldera ring faults: sand-box modeling of natural examples from Kamchatka, Russia. Bull Volcanol 67:457–468. https://doi.org/10.1007/s00445-004-0387-1

Bertelsen HS, Guldstrand F, Sigmundsson F et al (2021) Beyond elasticity: are Coulomb properties of the Earth's crust important for volcano geodesy? J Volcanol Geotherm Res 410:107153. https://doi.org/10.1016/J.JVOLGEORES.2020.107153

Biggs J, Pritchard ME (2017) Global volcano monitoring: what does it mean when volcanoes deform? Elements 13:17–22. https://doi.org/10.2113/GSELEMENTS.13.1.17

Bindeman I (2008) Oxygen isotopes in mantle and crustal magmas as revealed by single crystal analysis. Rev Mineral Geochem 69:445–478. https://doi.org/10.2138/RMG.2008.69.12

Bowen NL (1948) The granite problem and the method of multiple prejudices. In: Giluly J (ed) Origin of granite. Geological Society of America Memoirs, pp 79–80

Boyce AJ, Fulignati P, Sbrana A (2003) Deep hydrothermal circulation in a granite intrusion beneath Larderello geothermal area (Italy): constraints from mineralogy, fluid inclusions and stable isotopes. J Volcanol Geotherm Res 126:243–262. https://doi.org/10.1016/S0377-0273(03)00150-1

Brown M (1994) The generation, segregation, ascent and emplacement of granite magma: the migmatite-to-crustally-derived granite connection in thickened orogens. Earth Sci Rev 36:83–130. https://doi.org/10.1016/0012-8252(94)90009-4

Burchardt S, Galland O (2016) Studying volcanic plumbing systems – multidisciplinary approaches to a multifaceted problem. In: Updates in volcanology - from volcano modelling to volcano geology

Burchardt S (2018) Introduction to volcanic and igneous plumbing systems-developing a discipline and common concepts. In: Volcanic and igneous plumbing systems: understanding magma transport, storage, and evolution in the Earth's crust. Elsevier, pp 1–12

Burchardt S, Walter TR, Tuffen H (2018) Growth of a volcanic edifice through plumbing system processes—volcanic rift zones, magmatic sheet-intrusion swarms and long-lived conduits. Volcan Igneous Plumb Syst:89–112. https://doi.org/10.1016/B978-0-12-809749-6.00004-2

Cashman K (1988) Crystallization of Mount St. Helens dacite: a quantitative textural approach. Bull Volcanol 50:194–209

Cashman KV, Sparks RSJ, Blundy JD (2017) Vertically extensive and unstable magmatic systems: a unified view of igneous processes. Science (80-). https://doi.org/10.1126/science.aag3055

Christensen NI, Salisbury MH (1975) Structure and constitution of the lower oceanic crust. Rev Geophys 13:57–86. https://doi.org/10.1029/RG013I001P00057

Coleman DS, Gray W, Glazner AF (2004) Rethinking the emplacement and evolution of zoned plutons: geochronologic evidence for incremental assembly of the Tuolumne Intrusive Suite, California. Geology 32:433–436. https://doi.org/10.1130/G20220.1

Cooper KM, Kent AJR (2014) Rapid remobilization of magmatic crystals kept in cold storage. Nature 506:480–483. https://doi.org/10.1038/nature12991

Cruden AR, Weinberg RF (2018) Mechanisms of magma transport and storage in the lower and middle crust—magma segregation, ascent and emplacement. In: Volcanic and igneous plumbing systems

de Saint Blanquat M, Horsman E, Habert G, Morgan S, Vanderhaeghe O, Law R, Tikoff B (2011) Multiscale magmatic cyclicity, duration of pluton construction, and the paradoxical relationship between tectonism and plutonism in continental arcs: Tectonophysics, 500:20–33

Drymoni K, Browning J, Gudmundsson A (2020) Dyke-arrest scenarios in extensional regimes: insights from field observations and numerical models, Santorini, Greece. J Volcanol Geotherm Res 396:106854. https://doi.org/10.1016/J.JVOLGEORES.2020.106854

Ebinger CJ, Keir D, Ayele A et al (2008) Capturing magma intrusion and faulting processes during continental rupture: seismicity of the Dabbahu (Afar) rift. Geophys J Int 174:1138–1152. https://doi.org/10.1111/J.1365-246X.2008.03877.X/2/174-3-1138-FIG011.JPEG

Edmonds M, Cashman KV, Holness M, Jackson M (2019) Architecture and dynamics of magma reservoirs. Philos Trans R Soc A 377. https://doi.org/10.1098/RSTA.2018.0298

Eichelberger JC, Hayes DB (1982) Magmatic model for the Mount St Helens blast of May 18, 1980. J Geophys Res 87:7727–7738. https://doi.org/10.1029/JB087iB09p07727

Elliott HAL, Wall F, Chakhmouradian AR et al (2018) Fenites associated with carbonatite complexes: a review. Ore Geol Rev 93:38–59

Ernst RE, Head JW, Parfitt E et al (1995) Giant radiating dyke swarms on Earth and Venus. Earth-Sci Rev 39:1–58. https://doi.org/10.1016/0012-8252(95)00017-5

Ernst RE, Dickson AJ, Bekker A (eds) (2021) Large igneous provinces: a driver of global environmental and biotic changes. Wiley

Galland O, Bertelsen HS, Eide CH et al (2018) Storage and transport of magma in the layered crust—formation of sills and related flat-lying intrusions. Volcan Igneous Plumb Syst. https://doi.org/10.1016/B978-0-12-809749-6.00005-4

Ganino C, Arndt NT, Zhou MF et al (2008) Interaction of magma with sedimentary wall rock and magnetite ore genesis in the Panzhihua mafic intrusion, SW China. Mineral Deposita 43:677–694. https://doi.org/10.1007/s00126-008-0191-5

Glazner AF (2021) Thermal constraints on the longevity, depth, and vertical extent of magmatic systems. Geochem Geophys Geosyst 22:e2020GC009459. https://doi.org/10.1029/2020GC009459

Glazner AF, Bartley JM, Coleman DS (2016) We need a new definition for 'magma'. EOS Trans Am Geophys Union 97. https://doi.org/10.1029/2016EO059741

Gudmundsson MT, Jónsdóttir K, Hooper A et al (2016) Gradual caldera collapse at Bárdarbunga volcano, Iceland, regulated by lateral magma outflow. Science (80-) 353. https://doi.org/10.1126/science.aaf8988

Guldstrand F, Galland O, Hallot E, Burchardt S (2018) Experimental constraints on forecasting the location of volcanic eruptions from pre-eruptive surface deformation. Front Earth Sci. https://doi.org/10.3389/feart.2018.00007

Hoek JD, Seitz HM (1995) Continental mafic dyke swarms as tectonic indicators: an example from the Vestfold Hills, East Antarctica. Precambrian Res 75:121–139. https://doi.org/10.1016/0301-9268(95)80002-Y

Holness MB, Humphreys MCS (2003) The Traigh Bhàn na Sgùrra Sill, Isle of Mull: flow localization in a major magma conduit. J Petrol 44:1961–1976. https://doi.org/10.1093/PETROLOGY/EGG066

Huber C, Townsend M, Degruyter W, Bachmann O (2019) Optimal depth of subvolcanic magma chamber growth controlled by volatiles and crust rheology. Nat Geosci 12:762–768. https://doi.org/10.1038/s41561-019-0415-6

Humphreys MCS, Smith VC, Coumans JP et al (2021) Rapid pre-eruptive mush reorganisation and atmospheric volatile emissions from the 12.9 ka Laacher See eruption, determined using apatite. Earth Planet Sci Lett 576:117198. https://doi.org/10.1016/J.EPSL.2021.117198

Huppert HE, Sparks RSJ (1981) The fluid dynamics of a basaltic magma chamber replenished by influx of hot, dense ultrabasic magma. Contrib Mineral Petrol 1980 753 75:279–289. https://doi.org/10.1007/BF01166768

Huppert HE, Turner JS (1981) A laboratory model of a replenished magma chamber. Earth Planet Sci Lett 54:144–152. https://doi.org/10.1016/0012-821X(81)90075-3

Huppert HE, Sparks RSJ, Turner JS (1983) Laboratory investigations of viscous effects in replenished magma chambers. Earth Planet Sci Lett 65:377–381. https://doi.org/10.1016/0012-821X(83)90175-9

Hutton DHW (1996) The 'space problem' in the emplacement of granite. Episodes 19:114–119. https://doi.org/10.18814/epiiugs/1996/v19i4/004

Jackson MD, Blundy J, Sparks RSJ (2018) Chemical differentiation, cold storage and remobilization of magma in the Earth's crust. Nature 564, 405–409.https://doi.org/10.1038/s41586-018-0746-2

Kavanagh JL (2018) Mechanisms of magma transport in the upper crust—dyking. Volcanic and igneous plumbing systems: understanding magma transport, storage, and evolution in the Earth's crust, Elsevier

Kavanagh JL, Engwell SL, Martin SA (2018) A review of laboratory and numerical modelling in volcanology. Solid Earth 9:531–571. https://doi.org/10.5194/se-9-531-2018

King M, Member H, David A et al (1957) Mechanics of hydraulic fracturing. Trans AIME 210:153–168. https://doi.org/10.2118/686-G

Köpping J, Magee C, Cruden AR et al (2022) The building blocks of igneous sheet intrusions: insights from 3-D seismic reflection data. Geosphere 18:156–182. https://doi.org/10.1130/GES02390.1

Kruger W, Latypov R (2020) Fossilized solidification fronts in the Bushveld Complex argue for liquid-dominated magmatic systems. Nat Commun 111 11:1–11. https://doi.org/10.1038/s41467-020-16723-6

Kavanagh JL, Annen CJ, Burchardt S, Chalk C, Gallant E, Morin JS, Williams R (2022) Volcanologists - Who are we and where are we going? Bull Volcanol (in press)

Krumbholz M, Hieronymus CF, Burchardt S et al (2014) Weibull-distributed dyke thickness reflects probabilistic character of host-rock strength. Nat Commun 5:1–7. https://doi.org/10.1038/ncomms4272

Lees JM (2007) Seismic tomography of magmatic systems. J Volcanol Geotherm Res 167:37–56. https://doi.org/10.1016/j.jvolgeores.2007.06.008

Magee C, Muirhead JD, Karvelas A et al (2016) Lateral magma flow in mafic sill complexes. Geosphere 12. https://doi.org/10.1130/GES01256.1

Marinoni LB (2001) Crustal extension from exposed sheet intrusions : review and method proposal. J Volcanol Geotherm Res 107(1–3):27–46

Marsh B (2004) A magmatic mush column Rosetta stone: the McMurdo Dry Valleys of Antarctica. Eos (Washington DC) 85:497–502

Martin SA, Kavanagh JL, Biggin AJ, Utley JEP (2019) The origin and evolution of magnetic fabrics in mafic sills. Front Earth Sci 7:64. https://doi.org/10.3389/FEART.2019.00064/BIBTEX

Mattsson T, Burchardt S, Almqvist BSG, Ronchin E (2018) Syn-emplacement fracturing in the Sandfell laccolith, eastern Iceland—implications for rhyolite intrusion growth and volcanic hazards. Front Earth Sci 6:5. https://doi.org/10.3389/feart.2018.00005

McNutt SR (2005) Volcanic seismology. Annu. Rev. Earth Planet Sci 32:461–491. https://doi.org/10.1146/ANNUREV.EARTH.33.092203.122459

Morton BR, Taylor G, Turner JS (1956) Turbulent gravitational convection from maintained and instantaneous sources. Proc R Soc London Ser A Math Phys Sci 234:1–23. https://doi.org/10.1098/RSPA.1956.0011

Neal CA, Brantley SR, Antolik L et al (2019) Volcanology: the 2018 rift eruption and summit collapse of Kilauea Volcano. Science (80-) 363:367–374. https://doi.org/10.1126/SCIENCE.AAV7046/SUPPL_FILE/PAPV2.PDF

Norcliffe J, Magee C, Jackson CAL et al (2021) Fault inversion contributes to ground deformation above inflating igneous sills. Volcanica 4:1–21. https://doi.org/10.30909/VOL.04.01.0121

Paulatto M, Moorkamp M, Hautmann S et al (2019) Vertically extensive magma reservoir revealed from joint inversion and quantitative interpretation of seismic and gravity data. J Geophys Res Solid Earth 124:11170–11191. https://doi.org/10.1029/2019JB018476

Petford N, Cruden AR, McCaffrey KJW (2000) Vigneresse JL (2000) Granite magma formation, transport and emplacement in the

Earth's crust. Nat 4086813(408):669–673. https://doi.org/10.1038/35047000
Polteau S, Mazzini A, Galland O et al (2008) Saucer-shaped intrusions: occurrences, emplacement and implications. Earth Planet Sci Lett 266:195–204. https://doi.org/10.1016/J.EPSL.2007.11.015
Poppe S, Gilchrist J, Breard ECP, Graettinger A, Pansino S (2022) Analog experiments in volcanology: towards quantitative, upscaled and integrated models. Bull Volcanol (in press)
Pritchard ME, de Silva SL, Michelfelder G et al (2018) Synthesis: PLUTONS: investigating the relationship between pluton growth and volcanism in the Central Andes. Geosphere 14:954–982. https://doi.org/10.1130/GES01578.1
Putirka KD (2008) Thermometers and barometers for volcanic systems. Rev Mineral Geochem 69:61–120. https://doi.org/10.2138/rmg.2008.69.3
Read HH (1957) The granite controversy. Interscience, New York
Rhodes EL, Barker AK, Burchardt S et al (2021) Rapid assembly and eruption of a shallow silicic magma reservoir, Reyðarártindur Pluton, Southeast Iceland. Geochem Geophys Geosyst 22. https://doi.org/10.1029/2021GC009999
Rout SS, Blum-Oeste M, Wörner G (2021) Long-term temperature cycling in a shallow magma reservoir: insights from sanidine megacrysts at Taápaca volcano, Central Andes. J Petrol 62:1–32. https://doi.org/10.1093/PETROLOGY/EGAB010
Russell JK, Stephen J, Sparks R, Kavanagh JL (2019) Kimberlite volcanology: transport, ascent, and eruption. Elements 15:405–410. https://doi.org/10.2138/GSELEMENTS.15.6.405
Scarpa R, Gasparini P (1996) A review of volcano geophysics and volcano-monitoring methods. Monit Mitig Volcano Hazards:3–22. https://doi.org/10.1007/978-3-642-80087-0_1
Schmiedel T, Burchardt S, Mattsson T et al (2021) Emplacement and segment geometry of large, high-viscosity magmatic sheets. Minerals 11. https://doi.org/10.3390/min11101113
Senger K, Millett J, Planke S et al (2017) Effects of igneous intrusions on the petroleum system: a review. First Break 35. https://doi.org/10.3997/1365-2397.2017011
Sibbett BS (1988) Size, depth and related structures of intrusions under stratovolcanoes and associated geothermal systems. Earth-Sci Rev 25:291–309. https://doi.org/10.1016/0012-8252(88)90070-0
Sigmundsson F, Hreinsdóttir S, Hooper A et al (2010 4687322) Intrusion triggering of the 2010 Eyjafjallajökull explosive eruption. Nature 468:426–430. https://doi.org/10.1038/nature09558
Sigmundsson F, Hooper A, Hreinsdóttir S et al (2014) Segmented lateral dyke growth in a rifting event at Bárðarbunga volcanic system, Iceland. Nature 517:191–195. https://doi.org/10.1038/nature14111
Sigmundsson F, Parks M, Pedersen R et al (2018) Magma movements in volcanic plumbing systems and their associated ground deformation and seismic patterns. Volcan Igneous Plumb Syst:285–322. https://doi.org/10.1016/B978-0-12-809749-6.00011-X
Sillitoe RH (2010) Porphyry copper systems. Econ Geol 105:3–41. https://doi.org/10.2113/gsecongeo.105.1.3
Spacapan JB, Galland O, Leanza HA, Planke S (2017) Igneous sill and finger emplacement mechanism in shale-dominated formations: a field study at Cuesta del Chihuido, Neuquén Basin, Argentina. J Geol Soc Lond. https://doi.org/10.1144/jgs2016-056
Spacapan JB, Palma JO, Galland O et al (2018) Thermal impact of igneous sill-complexes on organic-rich formations and implications for petroleum systems: a case study in the northern Neuquén Basin, Argentina. Mar Pet Geol. https://doi.org/10.1016/j.marpetgeo.2018.01.018
Sparks SRJ, Sigurdsson H, Wilson L (1977) Magma mixing: a mechanism for triggering acid explosive eruptions. Nature 2675609 267:315–318. https://doi.org/10.1038/267315a0
Sparks RSJ, Annen C, Blundy JD et al (2019) Formation and dynamics of magma reservoirs. Philos Trans R Soc A 377. https://doi.org/10.1098/RSTA.2018.0019
Spera FJ, Bohrson WA (2018) Rejuvenation of crustal magma mush: a tale of multiply nested processes and timescales. Am J Sci 318:90–140. https://doi.org/10.2475/01.2018.05
Srivastava RK, Ernst RE, Peng P (eds) (2019) Dyke swarms of the world: a modern perspective. Springer, Singapore
Stephens TL, Walker RJ, Healy D et al (2017) Igneous sills record far-field and near-field stress interactions during volcano construction: Isle of Mull, Scotland. Earth Planet Sci Lett 478:159–174. https://doi.org/10.1016/J.EPSL.2017.09.003
Stimac J, Goff F, Goff CJ (2015) Intrusion-related geothermal systems. In: The encyclopedia of volcanoes. Elsevier, pp 799–822
Svensen HH, Planke S, Neumann ER et al (2018) Sub-volcanic intrusions and the link to global climatic and environmental changes. Adv Volcanol:249–272. https://doi.org/10.1007/11157_2015_10
Thiele ST, Cruden AR, Zhang X et al (2021) Reactivation of magma pathways: insights from field observations, geochronology, geomechanical tests, and numerical models. J Geophys Res Solid Earth 126:e2020JB021477. https://doi.org/10.1029/2020JB021477
Tibaldi A, Pasquarè FA (2008) A new mode of inner volcano growth: the "flower intrusive structure". Earth Planet Sci Lett 271:202–208. https://doi.org/10.1016/J.EPSL.2008.04.009
Turner JS, Huppert HE, Sparks RSJ (1983) An experimental investigation of volatile exsolution in evolving magma chambers. J Volcanol Geotherm Res 16:263–277. https://doi.org/10.1016/0377-0273(83)90033-1
Voight B, Sparks RSJ (2010) Introduction to special section on the Eruption of Soufrière Hills Volcano, Montserrat, the CALIPSO Project, and the SEA-CALIPSO Arc-Crust Imaging Experiment. https://doi.org/10.1029/2010GL044254
Voight B, Sparks RSJ, Shalev E et al (2014) The SEA-CALIPSO volcano imaging experiment at Montserrat: plans, campaigns at sea and on land, scientific results, and lessons learned. Geol Soc Mem 39:253–289. https://doi.org/10.1144/M39.15
Walker GPL (1992)"Coherent intrusion complexes" in large basaltic volcanoes—a new structural model. J Volcanol Geotherm Res 50(1-2):41–54
Walker GPL, Eyre PR (1995) Dike complexes in American Samoa. J Volcanol Geotherm Res 69:241–254. https://doi.org/10.1016/0377-0273(95)00041-0
White RS, Edmonds M, Maclennan J et al (2019) Melt movement through the Icelandic crust. Philos Trans R Soc A 377. https://doi.org/10.1098/RSTA.2018.0010
Wieser PE, Edmonds M, Maclennan J, Wheeler J (2020) Microstructural constraints on magmatic mushes under Kīlauea Volcano, Hawaiʻi. Nat Commun 111(11):1–14. https://doi.org/10.1038/s41467-019-13635-y