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

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Received: 15 July 2021 / Accepted: 8 April 2022 / Published online: 18 May 2022 © The Author(s) 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

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

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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, andMontserrat, 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.
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...
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

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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.
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 Bohrsen 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 subvertical 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 Bohrsen 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 rang-
ing 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 under-
standing of the physics behind the modelling process and
how appropriate the model output is to the natural phenom-
ena. 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 volcan-
ology at all (Burchardt 2018). For instance, igneous intru-
sions were studied by both structural geologists and igneous
petrologists, and the results were published in separate spe-
cialised journals for structural geology and igneous petro-
logy 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 mul-
tidisciplinary 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 erup-
tion of La Palma, Canary Islands.
2. scientific conference sessions, symposia, and work-
   shops 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 par-
ticular, 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 com-
plexity 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 over-
come their weaknesses such that the whole is greater than
the sum of its parts (Burchard 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 special-
ised 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 envi-
sion 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
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).

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