RESEARCH METHODS

VOLCANICA

Submitted: 2024-06-12 | Accepted: 2024-12-04 | Published: 2025-02-27

# Magmatic trees: a method to compare processes between igneous systems

Christy B. Till*

School of Earth & Space Exploration, Arizona State University, Tempe AZ 85287-6004, USA.

## Abstract

This paper presents the motivation, instructions, and applications for a new graphical method to construct 'magmatic trees', which summarize the petrologic and geochemical processes that formed a particular igneous rock unit or eruption. The method is motivated by the need to develop new ways to compare and contrast igneous systems to address frontier research questions in volcano science. It is designed to be easily executed with common datasets, compel the integration of different data types, and facilitate cross-disciplinary conversations about the processes that underly these data (e.g. between the volcano remote sensing and petrology communities). There are numerous potential applications of the method, which include, a) motivating process-driven hypotheses, b) examining the frequency of particular magmatic processes within and among volcanic systems, c) building mantle and crustal magmatic processes into event trees for hazard assessment, and d) teaching petrologic methods. For example, constructing magmatic trees for successive eruptions at a volcano or for multiple volcanoes within the same tectonic setting not only helps quantify the probability of individual magmatic processes but leads to addressing higher-level questions, such as what crustal and magma characteristics cause the same set of processes to be repeated in successive eruptions at Mounts Hood, Unzen, Pinatubo, and Soufrière Hills, while different sets characterize magmas erupted at neighboring volcanoes like Mount St. Helens? In addition, one can imagine a future where machine learning removes much of the human error from magmatic process identification, as well as magmatic tree construction, thereby enhancing our ability to identify patterns of magmatic processes.

## Non-technical summary

This paper presents the instructions to draw charts of the processes that occur in magmas prior to their eruption or cooling below ground. These charts are named 'magmatic trees.' Different types of data, for example the chemistry of minerals and magmas and their temperatures of origin, are needed to draw the trees. These trees can be used to translate the interpretations from one type of study to volcano scientists who are familiar with different methods and data types, as well as identify holes in our understanding of how a particular volcano or set of volcanoes work. In addition, these trees can be used to reveal the processes most likely to occur in the future at a given volcano, as well as many other useful applications.

Keywords: Volcano classification; Magmatic processes; Mantle melting; Crustal melting; Crystallization; Eruption initation.

## 1 Introduction/Motivation

Today if one asks a room full of volcano scientists to identify the key processes that produced a specific mafic lava, the unique answers are likely to be as numerous as the scientists themselves. One scientist may focus on the magma's mantle origins based on phase equilibria experiments or radiogenic isotopes, while another may focus on its crustal storage history using information stored within its zoned phenocrysts and melt inclusions, and a third may focus on its ascent and degassing history using crystal size distributions, gas geochemistry, and/or remote sensing data. The proliferation of approaches to studying magmatic and volcanic behavior in the modern era mean that the types of data we collect, as well as their resolution, timescales, and length scales vary greatly, as do the types of interpretations we draw from them. Despite the many scientific advances this proliferation has garnered, it also poses challenges to building unified theories and models of igneous systems at present.

Humans have wrestled with the myriad forms and unpredictability of volcanic behavior for as long as we have been documenting eruptions (ca. 6200 B.C.E. [Sigurdsson 2000]). Simultaneously, our creation myths, folklore, and observations have sought to bring a sense of order and reason to our fiery neighbors. Ultimately, we must find ways to reconcile this age-old tension between a volcano's seemingly stochastic behavior (sometimes referred to as volcano "personality") and the belief that common processes underly such behavior if we are to move toward better forecasting magmatic and volcanic behavior [NASEM 2017; Brodsky et al. 2022].

Tackling grand challenges in volcano science such as these require that we find new and better methods to holistically compare and contrast igneous systems. Historically, volcano classification has primarily utilized morphological characteristics (e.g. stratocones, tuff ring, lava dome etc.) or styles of eruption (e.g. Plinian, Vulcanian, Strombolian etc.) [Scrope 1872; Rittmann 1962; Simkin and Siebert 1994]. While these classification schemes remain useful and have led to instrumental research in the last few decades, they also bias these classifications towards the processes that occur in the shallowest magma storage region and conduit. Thus, a variety of recent community planning documents all suggest we need to look beyond existing classification schema in order to define the next generation of theories and models of igneous systems [e.g. NASEM 2017; Brodsky et al. 2022]. Indeed, in a perspec-

* cbtill@asu.edu

Editor: J. Farquharson | Typesetter: J. Farquharson

tive paper Cashman and Biggs [2014] argue that volcanology is in need of a framework that integrates theory, experiments, and observational data and can span magma reservoirs from mantle to surface. A useful starting point to identifying new volcano science schema is to consider key methods used to organize complex information in other scientific fields.

### 1.1 Statistics and phylogenetics

Statistical clustering and classification techniques such as cladistics, the predecessor to phylogenetics, provide a useful point of comparison as we look to better scaffold igneous systems. Cladistics became popularized in the 1950s for use in evolutionary biology to group individual organisms with shared characteristics and an implied similar evolution to produce graphical trees [Darwin 1859; Hennig 1965]. This method is in some ways similar to the statistical technique of principal component analyses, as there is no intrinsic requirement for the relationships identified to be evolutionary in nature [Pearson 1901; Brower 2000; Brower and Schuh 2021]. Methodology either closely resembling or including cladistics also became popular in the fields of comparative and historical linguistics as early as the 1960s, as it is particularly useful for dealing with discretized qualitative descriptive characteristics [e.g. Hoenigswald 1960; Platnick and Cameron 1977]. Similarly, anthropology developed statistical cluster analysis [Driver and Kroeber 1932], which was famously applied to trait classification in early personality psychology [Cattell 1943].

Over time evolutionary biology, anthropology, and linguistics have recognized the limitations of these approaches, including their tendency to create spurious groupings for datasets with a small number of traits. In particular, biology and linguistics have largely replaced cladistics with phylogenetics, which uses multiple methods (parsimony, maximum likelihood estimation, expert judgement etc.) to construct trees and relationships and allows for evolution and the emergence or loss of traits, as well as incorporating time in branch lengths.

While these methods have not been adopted widely in the igneous petrology, geochemistry, and volcanology communities, there are a number of relevant examples of their application. For example, Hone et al. [2007] applied cladistic analysis to the compositional, eruptive, and morphological characteristics of 129 volcanic edifices in the Tohoku region of NE Japan (Figure 1A). This method was able to identify groups of volcanoes erupting similar compositions, which in turn influenced the associated eruptive style and landforms, such that it could be useful for classifying volcanoes where spatial distributions are important (e.g. deciding where to locate nuclear reactors and repositories). A greater number of studies have applied principal component analyses to magmatic systems [e.g. Thy and Esbensen 1993; Harpp and White 2001], including Ueki and Iwamori [2017] who applied it to the compositions of arc magmas from the Sengan Volcanic Cluster in NE Japan. Their results suggest 85 % of geochemical variation in these rocks can be described by features consistent with magma mixing (59 %), crystallization of olivine and pyroxene (20 %), and plagioclase (6 %). Alternatively, Pitcher and Kent [2019] used modified hierarchical clustering techniques to analyze a large bootstrapped geochemical dataset from the U.S. Cascades Arc to identify six arc segments (Figure 1B), similar to other studies employing statistical cluster analysis [e.g. Cortés et al. 2007; Brandmeier and Wörner 2016].

Note that in all these examples, the statistical classification techniques aid the investigators in grouping samples or volcanoes, while the underlying process interpretations come about through other means, in addition to depending on the availability of large datasets and particular data types.

### 1.2 Probability models

Instead of using statistical clustering techniques, another approach is to organize observations through a network of causal influences, or events, and their probabilities. For example, fault tree analysis, developed by Bell labs in the 1960s, evaluates risk by tracing backward in time through a cause chain to prioritize the factors leading to an event and is commonly used in safety and reliability engineering. Another common example is event trees, which are a graphical representation of events and their probabilities that illustrates the permutations of possible sequential events like branches of a tree (Figure 2). Event trees have proven useful for illustrating the probabilities of possible outcomes when a volcano becomes active and have been successfully used in short-term forecasts (minutes to weeks) of eruptions [e.g. Newhall 1982; 1984; Aspinall and Cooke 1998; Newhall and Hoblitt 2002; Cassidy et al. 2018].

Alternatively, when the number of influences is large and cause and effect is not understood, the use of Bayesian networks (or causal networks, 'nets' for short) has become increasingly popular across the physical sciences to determine the joint probability (and therefore dependence and causation) amongst the unique random variables in the model when a condition changes [e.g. Puga et al. 2015]. Pioneering applications of Bayesian networks included medical decision making, insurance risks, and climate change assessments [Spiegelhalter et al. 1993; Neil et al. 2005; Kousky and Cooke 2012]. Today, Bayesian networks are increasingly used for diagnostics, classification, and prediction, including in volcano science [e.g. Aspinall and Woo 2014; Hincks et al. 2014; Christophersen et al. 2018]. For example, Aspinall and Woo [2014] present three Bayesian Belief Networks formulated during unrest at Santorini in 2011–2012 that combine multiple strands of scientific and observational evidence to determine the likelihood of volcanic hazards and risks. Similarly, Hincks et al. [2014] provide an early demonstration of the efficacy of Bayesian inference by retroactively studying the precursory behavior to the 1976 volcanic crisis at La Soufrière volcano, Guadeloupe.

Drawbacks and challenges of these methods include their dependence on the amount of available data and/or the challenges inherent in using expert elicitation to assess probabilities. Despite their proven utility in hazard forecasting, like cladistics and statistical clustering, event trees and Bayesian networks do not implicitly require the identification of the underlying mechanisms or processes to assess the probability of specific events. That is, they can be purely empirical when the processes are poorly understood. Finally, given their application to eruption hazard forecasting, these methods have almost exclusively focused on magmatic events in the shallowest parts of a volcanic system to date, and do not historically

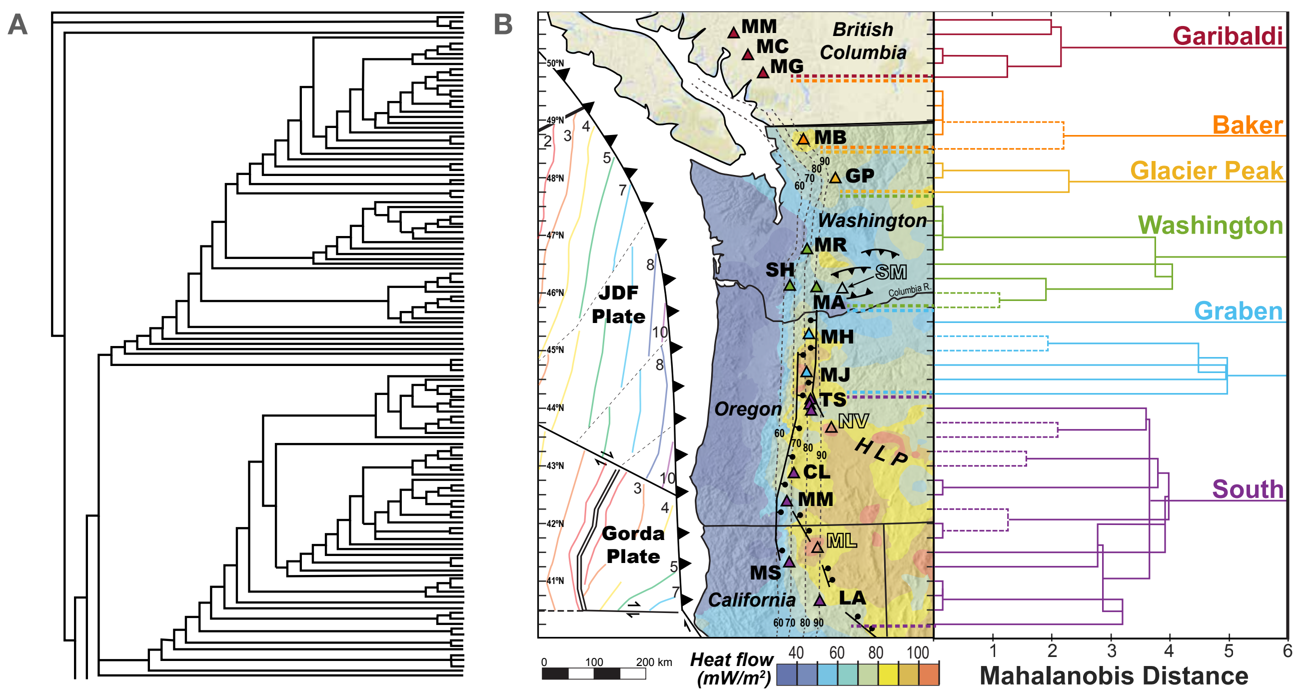


Figure 1: [A] Majority rule consensus tree produced by cladistics analysis of 129 volcanic centers in Tohoku Japan reproduced after Hone et al. [2007]. [B] Dendrogram produced by modified hierarchical clustering of a bootstrapped mean dataset for over 13,000 geochemical samples from the Cascades arc modified after Pitcher and Kent [2019]. See references for methodological details.

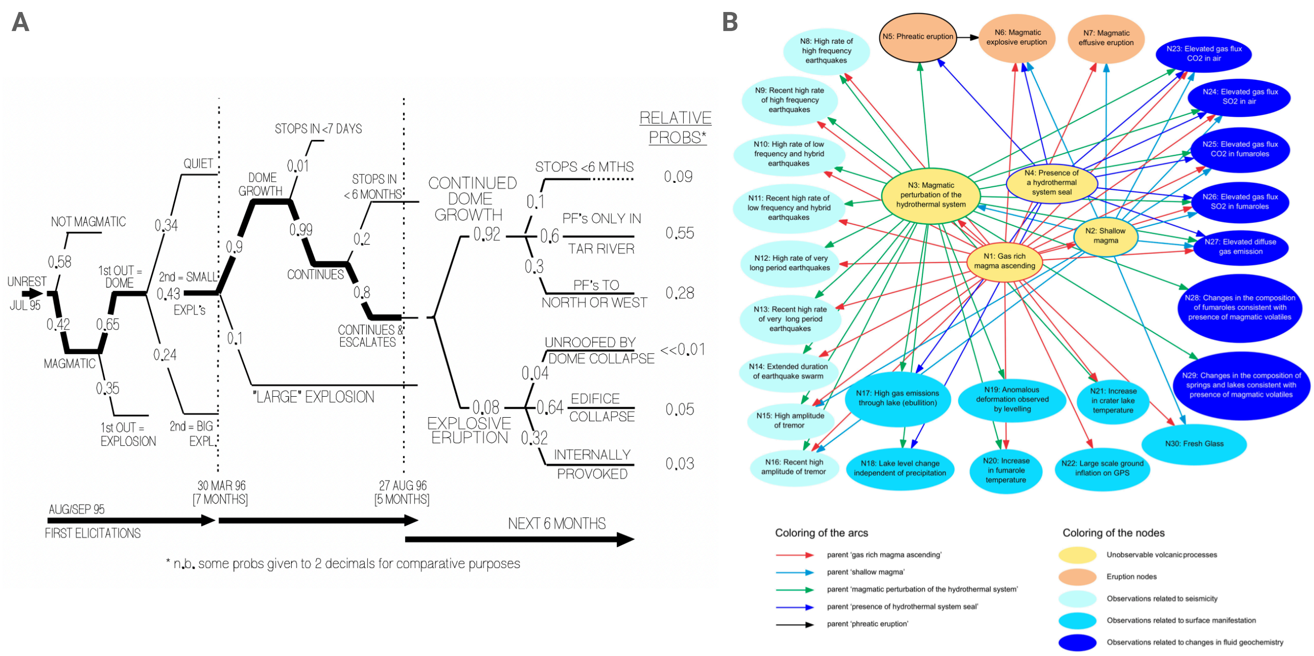


Figure 2: [A] Initial probability tree (or event tree) for the July 1995 eruption at Soufrière Hills, Montserrat, reproduced with kind permission from Aspinall and Cooke [1998]. Probabilities were calculated through expert elicitation. [B] Model structure of the Bayesian Network to forecast a volcanic eruption on Whakaari in the next month from Christophersen et al. [2018].

include processes that may occur at greater depths, despite their potential impact on eruptive behavior (see further discussion in Section 3).

### 1.3 A new graphical method: magmatic trees

We can see how each of the above classification schemes have proved valuable in complex fields, each with their associated limitations. Here, with the aim of advancing the conversation around how we compare and contrast igneous systems, I introduce a new graphical method to illustrate the key petrologic and geochemical processes that formed a particular magma (i.e. an igneous rock unit). This new method borrows attributes from several of the methods described above but is not purely empirical or probabilistic. Instead, it is based on the premise that a family of common processes underly magmatic and volcanic behavior, and that we can learn a great deal by centering a new method on their identification, frequency, and co-occurrence. By requiring particular types of interpretive decisions about underlying processes, this method enable the origins of different magmas to be easily compared. And unlike cladistics, phylogenetics, or other statistical clustering techniques, this method is not biased towards use with datasets of a particular type or size, enabling wide applicability. The focus on process also allows it to be integrated with probabilistic models such as event trees, if desired.

I am going to refer to this chart of igneous processes as a 'magmatic tree'. The magmatic trees presented here are designed to have a basic essential structure to facilitate comparison of the processes giving rise any igneous rock unit but can also be amended to increase their detail and complexity, depending on the datasets available. This flexibility also allows the method to incorporate processes that occur at any point between a magma's birth and final cooling. The essential structure of magmatic trees and the processes they include are described in Section 2. Section 3 presents several useful applications, and Section 4 identifies future directions for utilizing magmatic trees.

## 2 Constructing a tree of igneous processes

### 2.1 Magmatic tree construction

Today, magmatic systems are thought to extend from the mantle to surface and often span the entire crust in continental settings (often referred to as 'trans-crustal magmatic systems'). These often complex systems are governed by both internal characteristics (e.g. magma composition, density, volatile content) and dynamic processes (e.g. magma mixing and crystallization), which can prime or initiate volcanic eruptions, as well as external characteristics (e.g. crustal composition, rheology, stress state) and processes (e.g. glacial unloading, earthquakes, edifice collapse), which can also act as eruption drivers for primed systems. Magmatic trees are designed to only illustrate the *internal processes* operating in magmatic systems, specifically those which can be readily identified via the modern petrologic and geochemical study of igneous rocks.

This section walks step-by-step through the predominant internal processes thought to govern the formation and evolution of a magma or igneous rock unit and provides a high-level overview of the petrologic or geochemical methods to identify each of these processes or map them on a magmatic tree. The most common envisioned application is the creation of a tree to illustrate the processes that produced an individual eruption (i.e. an individual volcanic rock unit). In this case, the tree is constructed using evidence derived from an individual eruptive deposit (e.g. lava flow), or series of deposits (e.g. tephras and lavas) produced over the course of the same eruption. Section 3.3 discusses an alternative application, where a single tree is drawn to illustrate the sequences of processes that formed all the eruptions at a given volcano over a specified time period, with probabilities assigned to each process on the tree based on its frequency to turn the tree into a type of probabilistic event tree. In this case, the tree is constructed with evidence from samples or suites of samples from multiple eruptions. While the trees and discussions in this paper focus on the processes forming individual eruptions or volcanic rock units, they can also be easily adapted for use with plutonic rocks, for example by replacing the eruption initiation processes with those governing near and sub-solidus magmatic behavior.

The basic tree illustrated in Figure 3 is designed to function as a flow chart. The processes are broadly illustrated on the tree in the order in which they occur spatially, starting with mantle melting processes at the bottom and finishing with eruption initiation processes at the top. However, this is not strictly true, as crystallization and crustal melting or magma mixing may be occurring simultaneously, and/or occur repeatedly at different depths as the magma ascends. While magmatic trees are not designed to indicate the frequency of a particular process, rather only their presence/absence as a key player in the formation of a particular magma, you may wish to indicate that two or more processes occurred concurrently (as illustrated in Figure 4A) or duplicate levels of the tree to show the relative timing of repeat processes (as is illustrated in Figure 7). Two example trees are provided in Figure 4 (for a hydrous, high-Mg, arc andesite) and Figure 5 (for a nominally-anhydrous continental basalt), which will be used to illustrate tree construction in Sections 2.2–2.7. Figure 4 also illustrates two different interpretations regarding the origins of the same magma, demonstrating how magmatic trees can provide a quick visualization of the similarities and differences in interpretations between different studies. If you are already well versed in mantle and crustal igneous processes, you may wish to skip to Section 2.8, where further details of magmatic tree construction are discussed, or Section 3, which discusses useful applications of magmatic trees.

### 2.2 Mantle melting

We shall begin in the asthenospheric mantle, where in the simplest terms all magma begins life. The predominant mechanism for producing melt on Earth is decompression of the asthenospheric mantle (known as 'decompression melting'), as is the case for magmas formed at mid-ocean ridges, intraplate hot spots, and the back-arcs of subduction zones. Here, mantle rising along an adiabat crosses the nominally anhydrous mantle solidus and the difference of temperature between the

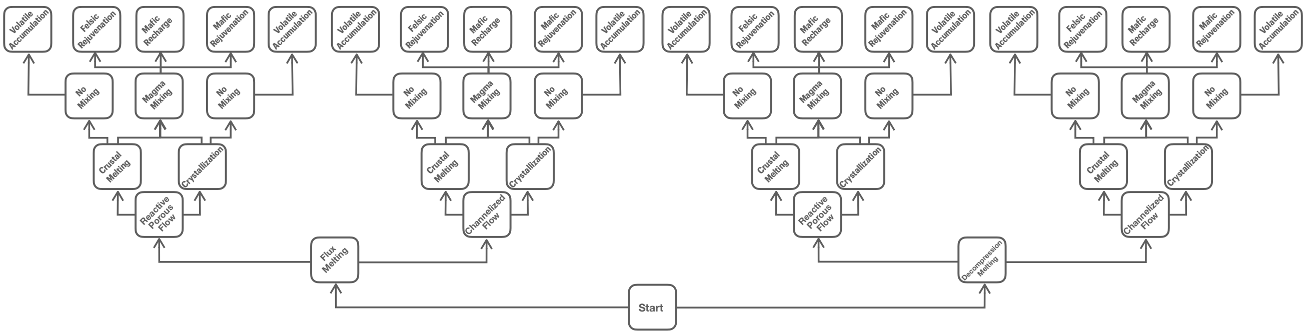


Figure 3: Basic magmatic tree structure.

adiabat and the lower temperature solidus provides the latent heat of fusion to drive melting, which increases in extent as the mantle approaches the surface. The higher mantle potential temperatures inferred for hot spots means that their adiabats intersect the nominally anhydrous mantle solidus at greater depths than mid-ocean ridge adiabats and lead to greater extents of melting [e.g. Putirka et al. 2007]. Overall decompression melting tends to produce nominally anhydrous tholeiitic basalts, with variations in the depth and extent of melting and the composition of the mantle producing variations in the resulting basalt major and trace element composition. Alternatively, mantle melts are produced by depression of the mantle solidus due to the introduction of volatiles, such as $H_2O$, $CO_2$, and $SO_2$ (known as 'flux melting'). More specifically, flux melting occurs when the system of interest is volatile-saturated, or when all the minerals present are saturated with the volatile phase such that a separate volatile phase is stabilized. The volatile concentration required for saturation can be calculated using expressions based volatile partitioning behavior (for $H_2O$-peridotite system see: Grove et al. [Equation 1 of 2006] and Till et al. [Table 1 of 2010]). This is the dominant mechanism for producing magmas erupted in volcanic arcs at subduction zones. Most commonly, flux melting begins due to the breakdown and dehydration of hydrous minerals, like those found in subducting crust or lithospheric mantle, where melting begins immediately upon introduction of the volatile phase (known as 'dehydration melting'). Overall flux melting tends to produce magmas with higher $SiO_2/(FeO^*+MgO)$ compared to decompression melting due to the lower melting temperatures, such that the primary flux melts of the mantle tend to be silicic basalts or andesites [e.g. Gaetani and Grove 1998]. For a more detailed review of these mantle melting processes, see Grove et al. [2012] and Grove and Till [2015].

A simple method to distinguish between a rock's origin via decompression versus flux melting is by plotting its whole rock major element composition on a Miyashiro discrimination diagram, which distinguishes between rocks of the tholeiitic versus calc-alkaline series, or the presence/absence of primary hydrous minerals such as amphibole in the rock (see Supplementary Material 1 for additional information). In the example in Figure 4, the whole rock major element composition of the Mount Shasta high-Mg andesite not only plots in Miyashiro's calc-alkaline field but is also similar to the composition of melts generated in peridotite and harzburgite flux-melting experiments [e.g. Mitchell and Grove 2015; Grove and Till 2019], leading several authors to interpret it to be the product of flux melting (Figure 4A). In Figure 5, the whole rock major element composition of the Oregon High Lava Plains basalt is tholeiitic and geochemical modeling by Till et al. [2012] suggests it was produced through 8 % batch melting of a nominally-anhydrous spinel lherzolite mantle at ~1.3 GPa, leading to the interpretation it was generated by decompression melting.

## 2.3 Mantle melt transport

Two endmembers describe how melt is transported away from its point of origin in the asthenospheric mantle: channelized flow and reactive porous flow. These two endmembers do not completely describe the complexity of our understanding of melt transport dynamics in the upper mantle [e.g. Wilson et al. 2014; Cerpa et al. 2018]. However, our ability to identify mechanisms of melt transport from geochemical and petrologic evidence preserved in erupted magmas is limited to these two endmembers at present. In channelized flow, which can be approximated as Stokes flow, the melt becomes isolated from the mantle, limiting chemical exchange with the mantle as it rises. Thus, the melt records the conditions of its origins at or near the solidus and is not subsequently overprinted by chemical re-equilibration. Evidence for channelized flow is abundant in nominally anhydrous magmas, which often record adiabatic ascent conditions from their solidus [Grove et al. 2002; Katz et al. 2022]. Alternatively, during reactive porous flow, which can be approximated as Darcy flow, melt rises through the network of mantle minerals and continues to re-equilibrate and change chemistry as it rises. Therefore, upon eruption or emplacement these magmas record the pressure, temperature, and bulk composition of the last point of mantle equilibration. Evidence for reactive porous flow is abundant in hydrous melts from subduction zones, which record their last equilibration with the mantle at conditions near the lithosphere-asthenosphere boundary [e.g. Grove et al. 2002; Till 2017; Grove and Till 2019]. Mantle thermobarometry of relatively unadulterated mantle-derived basalts is one useful way to determine their primary mantle transport mech-

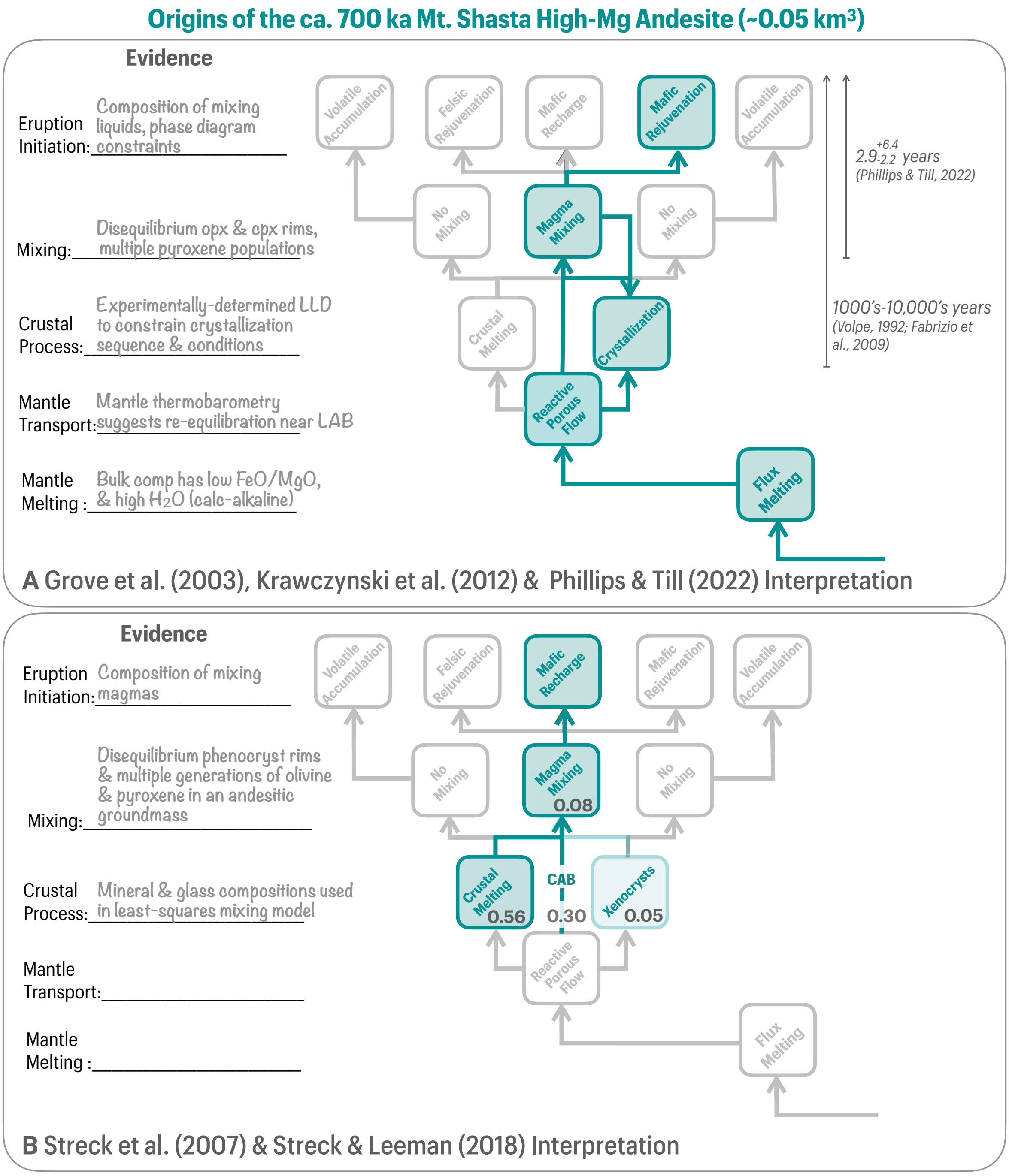


Figure 4: Example magmatic trees and the associated petrologic and/or geochemical evidence for two different hypotheses regarding the origins of the high-Mg andesite erupted at Mt. Shasta. Panel [A] is based on the data and interpretations in Grove et al. [2003], Krawczynski et al. [2012], and Phillips and Till [2022] and panel [B] on those in Streck et al. [2007] and Streck and Leeman [2018]. Geochronologic constraints from referenced studies in panel [A], and gray bold numbers in panel [B] denote percentage of crystal cargo arising from each process based mixing calculations in Streck and Leeman [2018]. Streck and Leeman [2018] do not discuss the origins of the calc-alkaline basalt used in their mixing model, which is why the mantle melting and melt transport mechanisms are not specified.

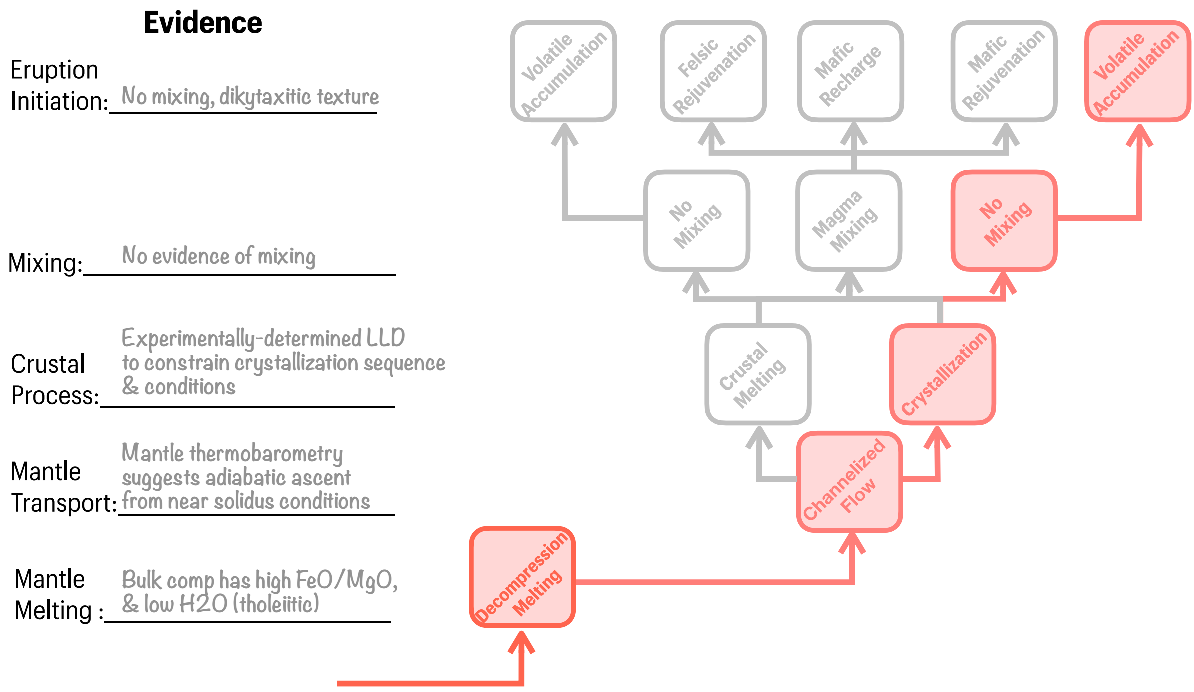


Figure 5: Example magmatic tree and the associated petrologic and/or geochemical evidence for a high alumina olivine tholeiitic basalt erupted in the Oregon High Lava Plains. Data from Till et al. [2012, 2013].

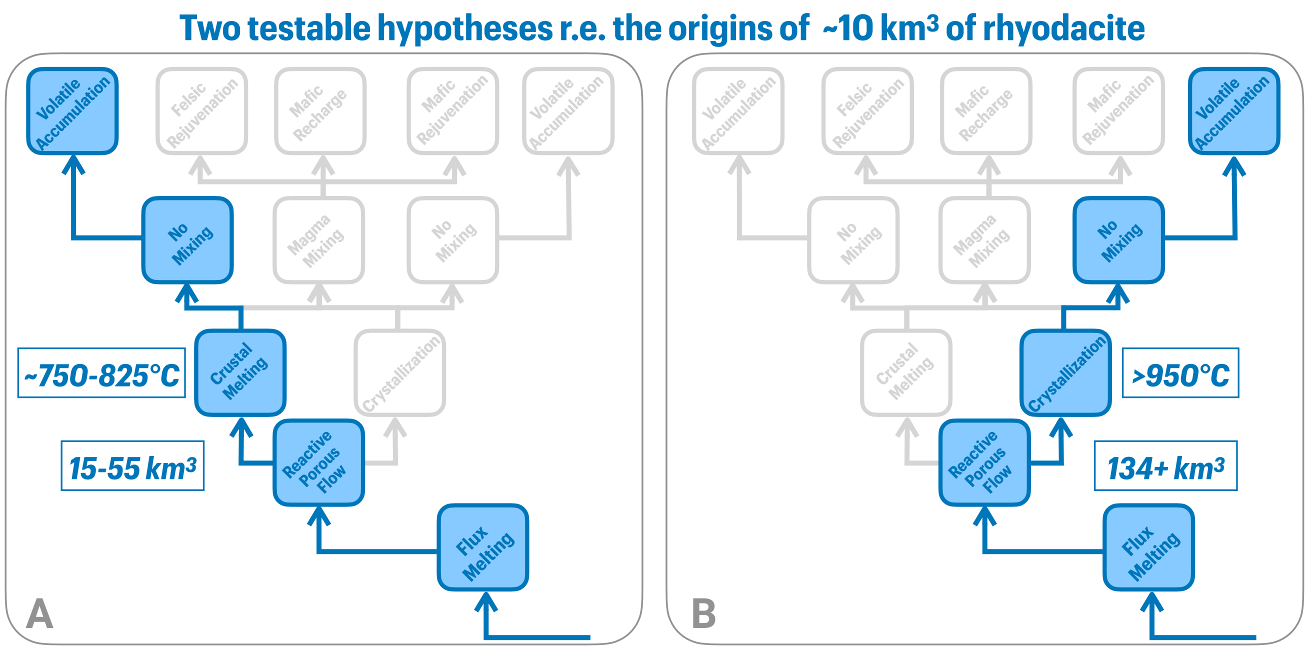


Figure 6: Cartoon illustrating two testable hypotheses regarding the possible origins of ~10 km$^3$ of rhyodacite erupted rhyolite at Glacier Peak. [A] Rhyodacites are generated through dehydration melting of crustal amphibolite, which requires 15–55 km$^3$ of mantle-derived magma depending on the thermal state of the amphibolite, at temperatures of 750–825 °C [Wolf and Wyllie 1994]. [B] Rhyodacites are generated exclusively through fractional crystallization, which would require 134 km$^3$ of mantle-derived magma or more, at temperatures of >950 °C [Till et al. 2019]. Hypothesis B would heat the surrounding crust significantly more than Hypothesis A. Calculations based on methods in Till et al. [2019].

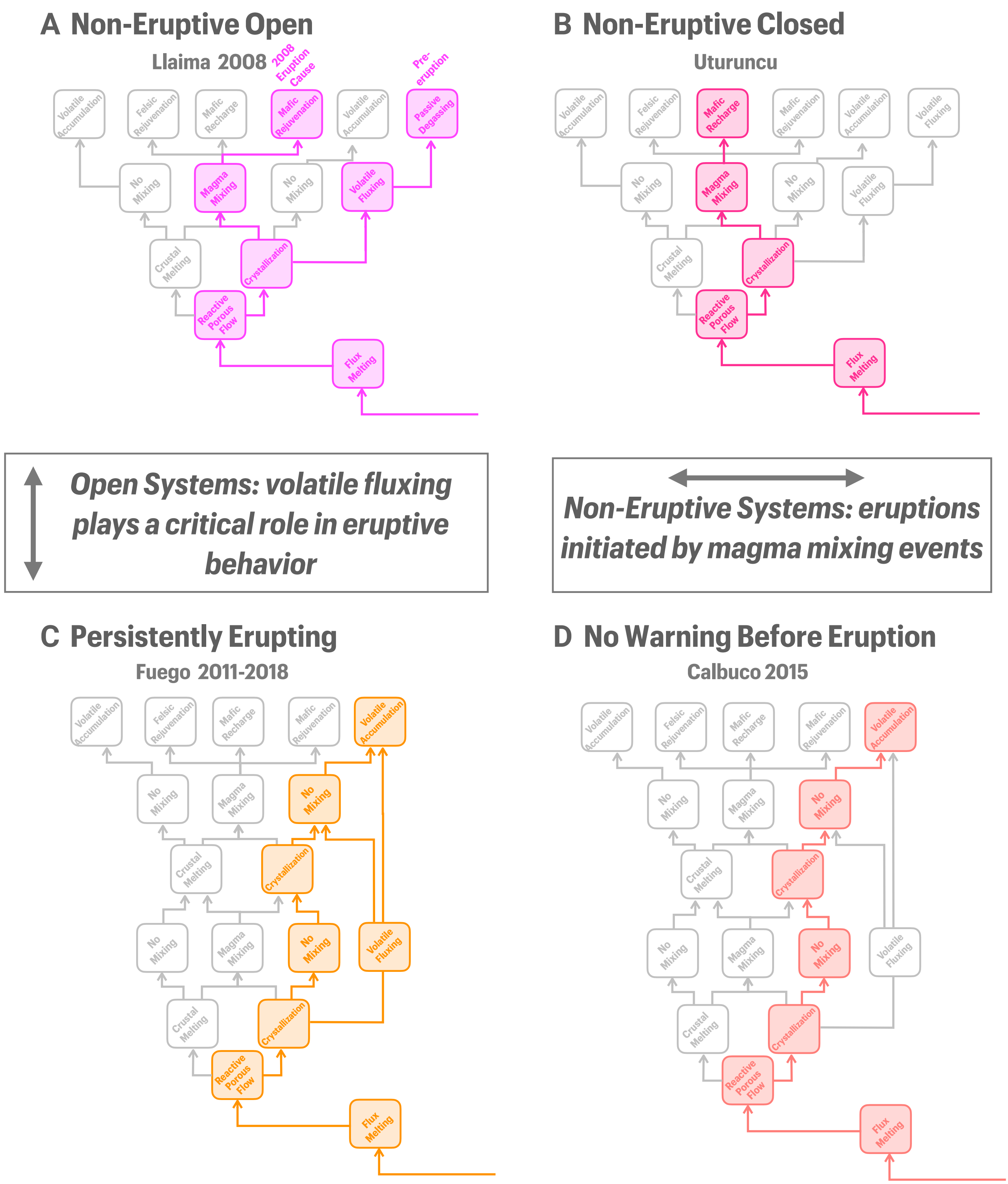


Figure 7: Magmatic trees constructed using petrologic studies of four active Central and South American stratocones with deformation, outgassing and thermal satellite data from 2000–2016 analyzed by Reath et al. [2019, 2020]. [A] Magmatic tree for the 2008 eruption of Lliama volcano based on work of Ruth et al. [2016]. [B] Magmatic tree for Uturuncu between 2000 and 2017 based on the work of Muir et al. [2014a,b].[C] Magmatic tree for the 2011–2018 eruptive period at Fuego volcano based on the work of Liu et al. [2020] and Harris and Anderson [1984]. Note the repetition of the 'crystallization' and 'no mixing' nodes based on the interpretation that these processes are occurring both in the lower and upper crust, while volatile degassing and subsequent fluxing exclusively originates from lower crustal storage regions. [D] Magmatic tree for the 2015 Calbuco eruption based on the work of Namur et al. [2020]. Note repetition of levels of the tree for reasons similar to that described for [C].

anism [e.g. Till et al. 2013; Till 2017; Krein et al. 2021], as is the study of magmas from extinct arc sections and exhumed lower crustal rocks [e.g. Jagoutz et al. 2011; Bouilhol et al. 2015; Delph et al. 2021; Ratschbacher et al. 2024]. Experiments by Mitchell and Grove [2016] on melt-rock reaction in the mantle wedge provide evidence for transporting the parental magma for the Shasta high-Mg andesite via reactive porous flow (Figure 4A) and mantle thermobarometry by Till et al. [2013] suggests the High Lava Plains parental magma was transported by channelized flow (Figure 5). However, collecting these types of evidence is not always practical. Given the considerable evidence for associating flux melting with reactive porous flow, and decompression melting with channelized flow, the more practical approach is to assume a melt transport mechanism based on the mantle melting mechanism (see Supplementary Material 1). Alternatively, one may choose to limit the designation of melt transport mechanisms in magmatic trees to applications where transport likely played a primary role in shaping the characteristics of the magma, compositional or otherwise.

### 2.4 Crystallization

At the lithosphere-asthenosphere boundary and in most cases again near the Mohorovičić discontinuity, magmas encounter rheologic boundaries, such that they may start to stall, accumulate, and/or mix to a greater degree than they do in the asthenospheric mantle. Magmas in the lithosphere and crust are prone to crystallization driven by either conductive heat loss and/or decompression. Unless a magma traverses the lithosphere extremely rapidly (i.e. hours to days), most magmas will experience at least some crystallization during ascent, as evident by the presence of crystals in an erupted igneous rock. The order, composition, and temperature at which minerals crystallize from a magma (also known as the 'liquid line of descent') is strongly dependent on pressure and the magma's bulk composition, volatile content, and oxygen fugacity, and has been studied extensively since the 1920s [e.g. Bowen 1928; Hamada and Fujii 2008; Blatter et al. 2013; Marxer et al. 2023]. The mantle melting mechanism that produced the rock will thus have a large effect on its liquid line of descent and magmatic tree. For example, magmas produced by flux melting tend to follow the calc-alkaline differentiation trend, which causes early crystallization of Cr-Al spinel or magnetite and lowers the temperature at which silicate minerals crystallize, plagioclase in particular, as well as altering the composition of crystallizing phases and coexisting melt relative to the tholeiitic differentiation trend [Grove and Baker 1984; Juster et al. 1989; Sisson and Grove 1993; Grove et al. 2003]. Other important liquids line of descent (also known as differentiation trends) include those for alkalic and carbonatitic magmas for example [e.g. Sack et al. 1987; Weidendorfer et al. 2017].

There are myriad approaches and computational tools to model crystallization and determine if it played a significant role in the formation of a particular igneous rock unit. These include mass and energy-balanced thermochemical models [e.g. Spera and Bohrson 2001], thermodynamic models such as `MELTS` [e.g. Ghiorso and Sack 1995; Gualda et al. 2012], and those that combine thermodynamic constraints with mass and energy conservation like the `Magma Chamber Simulator` [Bohrson et al. 2020]. More classically, curved arrays of whole rock or glass geochemistry from a single eruption, or series of eruptions, extending from a likely mafic parent magma composition on bivariate element plots can be a good indicator of crystallization, although it should be noted that the curvature of these arrays varies based on the crystallizing assemblage and bulk composition. Similarly, crystallization experiments on a bulk magma composition of interest or comparison of natural mineral compositions and assemblages to those in experiments are also useful for identifying crystallization trends (see Supplementary Material 1).

Returning to the Figure 4 example, experiments conducted by Krawczynski et al. [2012] at upper to mid-crustal pressures find that the Shasta high-Mg andesite was produced through crystallization of a mantle-derived magma with 10–14 wt.% $H_2O$. Modeling by Till et al. [2012] suggests the High Lava Plains basalt experienced low pressure crystallization of olivine + plagioclase. These interpretations lead to the 'crystallization' node to being selected on both magmatic trees (Figure 4A, Figure 5). In contrast, Streck et al. [2007] and Streck and Leeman [2018] interpret the crystals found in the Shasta high-Mg andesite to be mostly xenocrysts derived from nearby ultramafic rocks, older Shasta intrusions, and/or the conduit walls, such that they interpret crystallization to have played a much more minor role in the magma's formation. This alternate interpretation is indicated by the lighter color and labelling of the crystallization node on the tree in Figure 4B.

### 2.5 Crustal melting

When magmas enter the lithospheric mantle and crust, there is also the potential for them to assimilate or melt the surrounding host rock. As crystallization is an exothermic process, under many conditions, the intruding magma contains enough energy to generate crustal melt [e.g. Marsh 1984; Karakas and Dufek 2015]. Thus, crustal melting is a rare case where a magma can be said to begin its life in the crust rather than in the mantle. Crystallization and crustal melting often operate in tandem, although evidence of crustal contamination can be subtle and effect the system in ways not easily predicted by conventional intuition and simple mass balance arguments [e.g. Spera and Bohrson 2001; Annen et al. 2006; Bohrson et al. 2014]. The specific likelihood and extent of crustal melting in a given scenario depends on the ambient temperature of the crustal rocks, their bulk composition, and the temperature and volume of the intruding magma amongst other variables [e.g. Bohrson et al. 2020]. Crustal melting is more likely when the host rock contains a hydrous mineral, such as amphibole, that can contribute volatiles upon its breakdown to cause dehydration melting [e.g. Rushmer 1991; Wolf and Wyllie 1995]. Compilations of arc volcanic and plutonic rocks suggest most have seen some degree of mixing with melts derived from amphibole-bearing antecedent intrusions or lower crustal basement rocks [e.g. Blatter et al. 2013; 2017]. In some cases, basaltic underplating may contribute the heat to drive crustal melting with no subsequent mixing between the new crustal melt and the original mafic melts from the mantle. In cases where crustal melts have a contrasting composition to mantle-derived magma, the contribution of crustal melts can be detected with isotopic analyses (e.g. Th, Sr, Nd, O) or in some cases the rock's bulk Al/(2Ca+Na+K) (see Supplementary Material 1).

In the example magmatic trees, Streck et al. [2007] and Streck and Leeman [2018] use the core compositions of one pyroxene population along with rare dacitic pyroxene-hosted melt inclusions to infer that a crustal melt was one of the key components that formed the Shasta high-Mg andesite (Figure 4B), whereas crustal melting is not thought to have played a significant role in its formation by Grove et al. [2003] (Figure 4A).

### 2.6 Magma mixing

Magma mixing is another common magmatic process within the crust, and potentially within the mantle as well. Magma mixing can exist in a variety of forms, from the mixing of geochemically similar near-fractional melts to form the aggregate erupted magma in mid-ocean ridge environments, to the mixing of geochemically distinct magmas with unique crystal cargoes and volatile contents in the shallow crust beneath arc volcanoes. Even eruptions at monogenetic volcanic centers have been shown to have experienced cryptic, mid-crustal mixing with variably crystallized portions of the same parent magma [e.g. Phillips and Till 2022]. Thus, magma mixing may be fairly ubiquitous at some scale. For the purposes of creating a magmatic tree, the question is whether magma mixing was one of the primary igneous processes that shaped the rock's characteristics? Evidence for mechanical magma mixing of contrasting magma types shortly before eruption includes banded pumice, such as that from the 1915 eruption of Mount Lassen in California, compositionally zoned eruption deposits (i.e. zoned ignimbrites), and abundant magmatic enclaves or inclusions with crenulated (i.e. quenched) margins [e.g. Bacon 1986; Bacon and Druitt 1988; Clynne 1999; Tepley et al. 1999]. Evidence for magma mixing earlier in the magma's history can also include reversely zoned phenocrysts, disequilibrium mineral assemblages (e.g. quartz and olivine), dissolution textures, multiple populations of the same mineral with differing textures and/or compositions (e.g. four pyroxene andesites), and/or linear arrays of whole rock or glass compositions from a single eruption or a series of eruptions, which plot between the composition of two likely compositional endmembers on geochemical plots of two contrasting oxides or trace elements (see Supplementary Material 1).

Both sets of papers in the Figure 4 example interpret magma mixing to have played a significant role in the formation of the Shasta high-Mg andesite. Phillips and Till [2022] interpret reversely zoned rims on ortho- and clinopyroxene crystals to be the result of mixing more and less fractionated batches of the parent magma in the mid-crust (~975 °C & ~500 MPa) ca. three years prior to eruption based on Fe-Mg diffusion chronometry (Figure 4A). The extra arrow from 'magma mixing' to 'crystallization' in Figure 4A illustrates that these two processes are interpreted to have occurred concurrently. In contrast, Streck and coauthors interpret these same pyroxene crystals to reflect mixing between a crustal melt with a calc-alkaline basalt and use a linear least-squares mixing model to estimate the relative proportions of the mixing components, as shown in Figure 4B.

### 2.7 Eruption initiation

Finally, at the top of our basic magmatic tree is the choice of mechanisms that may initiate the final ascent and cooling of a magma (either via eruption or intrusion). There are a variety of processes that may cause a magma to go from stasis in the crust or lithosphere to final cooling, which can broadly be divided into internal and external mechanisms. Kent et al. [2023] conduct a meta-analysis of published studies constraining the internal magmatic processes initiating eruptions and find there are four key mechanisms: mafic recharge (mafic magma injecting more felsic magma), mafic rejuvenation (mafic magma injecting mafic magma), felsic rejuvenation (felsic magma injecting felsic magma), and volatile saturation (crystallization and cooling driving bubble nucleation and growth). Mafic and felsic rejuvenation cause eruptions when the injection rate outpaces viscous relaxation to produce sufficient overpressure to drive ascent and may be more common in thermally mature systems [e.g. Degruyter and Huber 2014; Caricchi et al. 2021]. Volatile saturation or accumulation, also known as second boiling, occurs when slowly cooling and crystallizing magmas within relatively elastic crust generate large-scale volatile exsolution and bubble growth to produce sufficient overpressure to drive eruptions [e.g. Sisson and Bacon 1999; Fowler and Spera 2008; 2010; Degruyter and Huber 2014]. Mafic recharge can cause overpressure by either mechanism, with volatile exosolution triggered by the contrasting thermal states of the mixing magmas likely dominating in younger volcanic systems, and the volume of injecting magma driving overpressure in more mature volcanic systems [e.g. Pallister et al. 1992; Kent et al. 2023]. Major or trace element or isotopic mineral zoning and types of crystal or liquid populations are excellent ways to identify the most likely eruption initiation mechanism for erupted magmas. The use of "most likely" here refers to the observation that not every occurrence of these events leads to an eruption. For example, reversely zones crystals, disequilibrium mineral assemblages (e.g. quartz and olivine) and/or multiple mineral populations (e.g. "four pyroxene andesites") are common indictors of mafic recharge [e.g. Eichelberger et al. 2006; Humphreys et al. 2009], but mafic recharge may occur repeatedly before sufficient overpressure is reached to drive ascent leading to eruption or may never lead to eruption in certain cases (see review by Caricchi et al. [2021] and references therein). However, if evidence for a particular eruption initiation mechanism exists in an erupted magma, it is inferred to be the *most likely* eruption initiation mechanism. Abundant enclaves, banded pumice and/or compositionally zoned deposits are other eruption-related indicators of mafic recharge. Mineral zoning and populations tend to be more subtle in the case of mafic or felsic rejuvenation, with mineral rims recording differences in temperature and trace element concentrations for example [e.g. Bachmann and Bergantz 2008; Shamloo and Till 2019] and/or glomerocrysts and strained crystals demonstrating evidence of disaggregation of crystal-rich mushes or cumulates [e.g. Wieser et al. 2020]. Evidence for volatile accumulation is the most cryptic in the petrologic record, which is likely why it is the mechanism with the least confirmed eruptions [Kent et al. 2023]. Evidence can be gleaned from variations in hydrous mineral abundances, fluid or melt inclusions, and crystals with normal zoning recording variations in fluid-mobile elements like Li [e.g. Kent et al. 2007; Andersen et al. 2018]. However, at present, volatile accumulation is often best identified through a process of elimination with other internal (and external) mechanisms for eruption initiation (see Supplementary Material 1).

As mentioned in the beginning of Section 2, there are also external mechanisms that initiate eruptions. These include near field phenomena such as roof collapse above large magma chambers [Gregg et al. 2012] and build-up of buoyancy forces [Caricchi et al. 2014; Malfait et al. 2014], as well as far field forcing related to large earthquakes [Cabaniss et al. 2018; Hamling and Kilgour 2020] and crustal unloading including via the removal of glaciers [e.g. Caricchi et al. 2021]. Although these mechanisms may be important in some settings, they are less likely to leave distinctive petrological or geochemical signatures in erupted products, other than an absence of evidence for other initiation mechanisms, such that it is difficult to determine their frequency. Thus, the emphasis for magmatic tree construction is first to identify any evidence for internal eruption initiation mechanisms, with external mechanisms being considered only in the absence of all other evidence.

Returning to our Figure 4 and Figure 5 examples one last time, the ubiquity of reversely-zoned phenocrysts formed within years of the eruption and the inference that these zoned crystals formed as a result of mixing between more and less fractionated versions of the same magma lead Phillips and Till [2022] to interpret that the eruption of the Shasta high-Mg andesite was initiated by mafic rejuvenation (Figure 4A). Alternatively, Streck and Leeman [2018] infer that the eruption was initiated by the injection of basalt into a reservoir of dacitic magma, which would be classified as mafic recharge by Kent et al. [2023] (Figure 4B). In the case of the High Lava Plains basalt, the lava records a dikytaxitic texture (lath-shaped arrangement of feldspar microlites around small vesicles) and no evidence for mixing, such that $CO_2$ accumulation is inferred to be the eruption initiation mechanism (Figure 5).

### 2.8 Further notes on magmatic tree construction

It is worth noting that there are numerous large- and small-scale igneous processes that have not been reviewed in this section and do not appear on the basic magmatic tree in Figure 3. Because of the focus on illustrating how to create a basic magmatic tree for most igneous rock types, the selection of igneous petrologic processes discussed here has been limited to those which are readily identifiable with a minimal and traditional dataset (i.e. hand sample description + petrography + whole rock major and trace element geochemistry ± mineral chemistry ± isotopic composition) by a student who has passed a college-level petrology course. However, magmatic trees can be easily adapted to include additional igneous processes when the necessary data is available, by outlining their identifying geologic characteristics (e.g. as is done in Supplementary Material 1) and adding another level to the tree in Figure 3. This is illustrated with the addition of volatile fluxing to the tree in Section 3.2 and Figure 7. Similarly, magmatic trees are not designed to illustrate the quantities involved in a given process, such as a magma's mass, volume, or geochemical composition. However, trees are set up in such a way that simple quantities or geochonologic constraints can be illustrated on the tree (e.g. see examples in Figures 4 and 6) and/or more mechanistic and quantitative models can easily be plugged into any given process node on the tree if desired, as discussed further in Section 3.5.

## 3 Example applications

There is perhaps no better way to make a case for the utility of magmatic trees than to sample a variety of potential applications and their benefits. While this section does not afford the space to go into any one application in significant or quantitative detail, it demonstrates how this conceptual graphical method can be useful for wide variety of purposes in volcano science including but not limited to, (1) identifying and testing process-related hypotheses regarding the origin of particular magmas, (2) recognizing common igneous processes producing the characteristics of distinct data types, (3) examining the frequency of a particular igneous processes between successive eruptions from the same volcano or across many volcanoes to create a type of event tree for crustal and mantle igneous processes, and (4) teaching igneous processes and their identifying characteristics. Through these examples we see that the focus on process inherent in their design compels us toward the multi-, and eventually inter-, disciplinary scientific approach we aspire to as a community, in addition to identifying key gaps in our understanding.

### 3.1 Testing between process-oriented hypotheses

In addition to providing an easily digestible visualization of petrologic interpretations, magmatic trees provide a means to set up process-oriented hypotheses and identify methods to test between them. As an example, consider the question of the origins of ~10 km$^3$ of rhyodacitic magma (average ~71 wt.% $SiO_2$) erupted from Glacier Peak Volcano in the Cascades Arc during the Quaternary. The volumetric implications of the two endmember processes capable of producing such silicic magma (i.e. crystallization and crustal melting) are quite distinct (Figure 6). Generating 10 km$^3$ of silicic magma via crustal melting requires ~10–50 km$^3$ of mantle-derived mafic magma to bring lower crustal basement rocks up to their solidus [e.g. Marsh 1984; Wolf and Wyllie 1994; Dufek and Bergantz 2005] and an additional ~5 km$^3$ to produce the ~10 km$^3$ melt (see calculations in Till et al. [2019]) (Figure 6A). This is in stark contrast to production of the silicic magma by pure crystal fractionation, which would require at least ~3× more mantle-derived mafic magma (~134 km$^3$ at 100% melt extraction from the crust) [Till et al. 2019] (Figure 6B). In addition, these two end-member processes may produce silicic magma at disparate temperatures based on experiments; ~750–825 °C via dehydration melting of amphibolite at 10 kbar [Wolf and Wyllie 1994] versus ≥~950 °C predicted for fractionation of damp to anhydrous mafic magmas (see Supplementary Figure S2 in Till et al. [2019]). Alternatively, Blatter et al. [2017] locate the amphibole = pyroxene +

melt peritectic reaction in basaltic bulk compositions at 925–940 °C at 700 or 900 MPa, which could be approached via melting or crystallization, and thus would not yield different temperatures for crustal melting versus crystallization. If present, a temperature differential between the crustal melting and crystallization scenarios, along with the volumetric considerations, means that silicic magma production via crustal melting (an endothermic process) would heat the crust substantially less than production via fractionation (an exothermic process). While the Glacier Peak rhyodacitic magmas (or any magma for that matter) were likely generated by a combination of these processes, the fact that the volumetric (± energetic) requirements for the two endmember processes are so distinct means that it may be possible to identify the dominant process in their formation by utilizing complimentary datasets such as $^{230}Th/^{238}U$ or $\delta^{18}O$ isotopic compositions of the erupted magmas and crystals, surface heat flow, and/or crustal seismic wave speeds [e.g. Bindeman et al. 2008; Feeley et al. 2008; Wende et al. 2015; Blatter et al. 2017]. This example thus shows how constructing magmatic trees for the generation of a particular magma type provides a means to identify process-oriented hypotheses and methods to test between them.

### 3.2 Integrating different data types into a cohesive process-based picture

In addition to prompting hypothesis testing, building magmatic trees also facilitates the integration of different data types to create a cohesive process-focused model of an igneous system. In fact, as apparent in Section 2, building complete trees *requires* the use of many types of data and can identify holes in our knowledge that could be filled by a given data type. To illustrate these points, petrologic and geochemical observations of active volcanoes in Latin America are used to build trees that reveal common processes behind their observed satellite characteristics in the following example.

In the last two decades satellite data has become an increasingly available and important dataset to document the characteristics of active volcanic systems globally. This data is especially useful for systems that are either hard to access and/or are poorly instrumented and understudied. In Reath et al. [2020], a multiparameter, multidecadal database of deformation, outgassing, and thermal satellite data is used to develop a classification scheme for the cause of unrest at the 47 most active volcanoes in Latin America. This classification effort identifies a volcano's eruptive state as 'open,' 'closed,' or 'eruptive' and the study goes on to classify these Latin American volcanoes as being in one of four categories: (1) dominantly non-eruptive closed, (2) dominantly non-eruptive open, (3) persistently erupting, (4) lacking sufficient data to categorize. For example, Llaima volcano is classified as being in a 'dominantly non-eruptive open' state between 2000 and 2016 when the volcano experienced deformation, outgassing, and a gradual decrease in thermal output, punctuated by a violent Strombolian eruption in 2008. Four stratovolcanoes are selected to draw magmatic trees for here, one from each of categories in Reath et al. [2020] ((1) Uturuncu, (2) Llaima, (3) Fuego, and (4) Calbuco), in order to interrogate the processes likely responsible for the satellite observations and classifications (Figure 7). As an example, the magmatic tree for the 2008 Strombolian eruption at Llaima volcano was constructed based on the petrologic study of Ruth et al. [2016], which found evidence in the tephra olivine-hosted melt inclusions for a single liquid line of descent produced by crystallization of hydrous arc-related magmas ("flux melting," "crystallization"), as well as volatile fluxing and passive degassing. Geochemical and textural evidence from the basalt to basaltic andesite lavas suggests that this crystallization occurred in a basaltic andesite crystal mush sustained by periodic, small-batch magma injections ("magma mixing"), one of which initiated the 2008 eruption ("mafic rejuvenation").

The magmatic trees constructed using the petrologic studies of these four volcanoes and their eruptions offer reasons for the satellite classifications (Figure 7). The trees reveal that both 'open' systems (Llaima and Fuego) exhibit evidence of volatile fluxing, consistent with work on eruption dynamics at silicic volcanoes [e.g. Eichelberger et al. 1986; Jaupart and Allègre 1991]. While this may seem unsurprising, it is significant that the petrologic studies find evidence of volatile exsolution and transport in samples capturing processes occurring at the last point of intra-crustal magma storage, which is distinct from the remote sensing data that records degassing from the conduit and/or surface (Figure 7). If we compare the two systems identified as 'dominantly non-eruptive' (Uturuncu and Calbuco), we see that both have eruptions caused by magma mixing processes, although the compositions involved differ. This is logical as magma mixing events can perturb 'non-eruptive' systems in stasis and under certain conditions initiate climatic eruptions by causing convective overturn, exsolution of volatiles, unlocking of crystal mushes, and/or overpressurization of magma reservoirs, among other processes [e.g. Cassidy et al. 2018; Kent et al. 2023].

These findings can then be tested by interrogating other eruptions in the Reath et al. [2020] dataset. For example, based on these generalizations, Cotopaxi—a stratocone classified as 'non-eruptive open'—should reveal evidence for volatile fluxing prior to its 2015 eruption. Similarly, there should be petrologic evidence that prior eruptions of the 'non-eruptive closed' Robledo caldera at Cerro Blanco volcanic complex were initiated by magma mixing events. Indeed, a combined seismic, gas geochemistry and petrologic study of the 2015 eruption at Cotopaxi finds that the magma experienced extensive sulfur exsolution and degassing during ascent and interacted with the shallow hydrothermal system to produce hydro-magmatic explosions [Hidalgo et al. 2018]. Likewise, work by de Silva et al. [2022] suggests andesitic recharge into a rhyolitic mush produced eruptions at Cerro Blanco over the last 54 kyr. Work by Geist and co-authors also supports a model whereby the two Galapagos volcanoes characterized as 'dominantly non-eruptive closed' have eruptions initiated by influxes of basaltic magma into upper crustal reservoirs containing more evolved magmas [Geist et al. 1995; 2014]. Thus, the initial findings regarding the petrologic processes producing the satellite classifications holds up to further scrutiny of additional systems and eruptions.

The construction of the magmatic tree for the "no warning" April 22, 2015 eruption of Calbuco also reveals why there were not any eruption indicators in the satellite data. Looking at the literature, Castruccio et al. [2016] and Morgado et al. [2019] both suggest a seismic event exploited existing crustal weaknesses to initiate the 2015 eruption, which requires that the magmatic system was primed for eruption and volatile accumulation is the most likely process to accomplish this [Hamling and Kilgour 2020]. Alternatively, Arzilli et al. [2019] and Namur et al. [2020] both conclude volatile accumulation in the shallowest magma storage region led to over-pressurization and failure of the overlying country rock to initiate the eruption. In either interpretation, it can be reasonably concluded that volatile accumulation played a critical role in initiating the eruption. And in $H_2O$-dominated arc magmatic systems such as Calbuco, as well as in systems where volatile accumulation does not lead to volatile fluxing, volatile accumulation has been shown to not lead to noticeable deformation, outgassing or thermal output [e.g. Yip et al. 2022].

Overall, this example demonstrates the utility of creating magmatic trees based on petrologic and geochemical research and their use in identifying the key magmatic processes producing the characteristics observed in satellite and volcano monitoring data. While this is by no means the first study to integrate satellite and petrologic data for the same eruption, this example is unique in highlighting the potential of doing this in a macro, multi-system, process-focused way, rather than through in-depth study of a single system, or multi-system compilations utilizing only one type of data. This example also highlights how magmatic trees provide a means to digest often complex and unique petrologic studies, such that their findings can be compared across volcanoes and eruptions, as well as easily understood by non-petrologists.

### 3.3 Magmatic trees as event trees

Another advantage of constructing magmatic trees is the opportunity to examine the frequency of a particular igneous process or set of processes between successive eruptions from the same volcano or across many volcanoes within a volcanic arc segment for example. Historically upper mantle and crustal igneous processes have been excluded from the probabilistic event trees used for hazard forecasting, which instead tend to focus on conduit and eruption processes and characteristics [e.g. Poland and Anderson 2020] (Figure 2). However, research in the last decade has documented substantial evidence that the events occurring in the shallowest crustal magma storage region, such as the four eruption initiation mechanisms discussed in Section 2.7, affect eruption behavior and characteristics such as eruption volume, style, frequency, and initiation timescales at continental volcanoes [e.g. Degruyter et al. 2016; Huber et al. 2019; Shamloo and Till 2019; Kent et al. 2023]. Similarly, there is now robust evidence for explosive basaltic eruptions being initiated from depths of 20 km or greater [e.g. Ruprecht and Plank 2013; Rasmussen et al. 2018; Mutch et al. 2019; Allison et al. 2021]. Constructing magmatic trees thus provides a method to build crustal and even mantle igneous processes into decision or event tree structures to assess the value and merit of including them in hazard forecasting.

As an example, andesitic lavas erupted at Mount Hood in the Cascades Arc over the past ~20,000 years are remarkably similar in composition and mineralogy. Petrologic research suggests they are all the product of mafic recharge of a silicic magma mush, which is thought to initiate each eruption [Kent et al. 2010; Koleszar et al. 2012]. Therefore, the magmatic trees of the processes forming each of these Mount Hood eruptions are identical, since only the amount of mixing and proportion of the mixing components are thought to vary between eruptions (Figure 8). If we assign probabilities to the processes at each level in Hood's magmatic tree based on the last 20,000 years of eruptions (i.e. convert it to an event tree), we see that there is a very high probability that this combination of processes will repeat in the event of a future eruption.

In contrast, there appears to be significantly more variation in the processes contributing to the magmas erupted since 1479 CE at Mount Hood's closest neighbor, Mount St. Helens. While Mount St. Helens predominantly erupts water-rich intermediate arc magmas like Mount Hood, the late-stage processes leading to eruption are thought to differ between eruptive periods (Figure 9). Work by Gardner et al. [1995a,b] and Leeman and Smith [2018] suggest that both Plinian eruptions and emplacement of andesitic lavas during the Kalama period (1479–1750 CE) were initiated by mafic recharge, whereas the 1980–86 eruptions are thought to have been initiated by felsic rejuvenation [Saunders et al. 2012] and the 2004–2008 dome-forming eruptions by volatile accumulation [Kent et al. 2007; Pallister et al. 2008]. Thus, the eruption initiation node on the tree for each of these eruptions would differ, and each would be assigned a lower probability of occurring in the future relative to mafic recharge at Mount Hood (Figure 9).

These probabilistic event trees are useful for improving our foundational knowledge of magmatic systems. As an illustration, constructing magmatic trees for successive eruptions and/or adjacent arc systems allows us to determine the propensity of certain upper mantle and/or crustal magmatic processes occurring together. For example, Mount Unzen, Soufrière Hills, and Mount Pinatubo, located in three distinct arcs, also exhibit similar behavior and magmatic trees to Mount Hood, repeatedly erupting compositionally similar andesitic magmas that all supply evidence for late-stage mafic recharge and magma mixing [Di Muro et al. 2008; Kayzar et al. 2009; Kent et al. 2010, and references therein]. By constructing trees for these systems, we can more easily see this pattern and identify higher-level questions, such as what crustal and magma characteristics cause the set of magmatic processes reproduced in many successive eruptions at Mounts Hood, Unzen, Pinatubo, and Soufrière Hills, but not at their nearby neighbors like Mount St. Helens?

Use of magmatic trees may also yield the identification of common suites of magmatic processes such as this example, that could ultimately become the basis for a new process-based volcano classification scheme. In these ways, magmatic trees could thus make substantive contributions to community grand challenges, such as developing models for the processes governing volcanic eruptions as articulated by the National Academies ERUPT report [2017], or frontier research questions such as, "what drives volcanism?" as recently articulated by

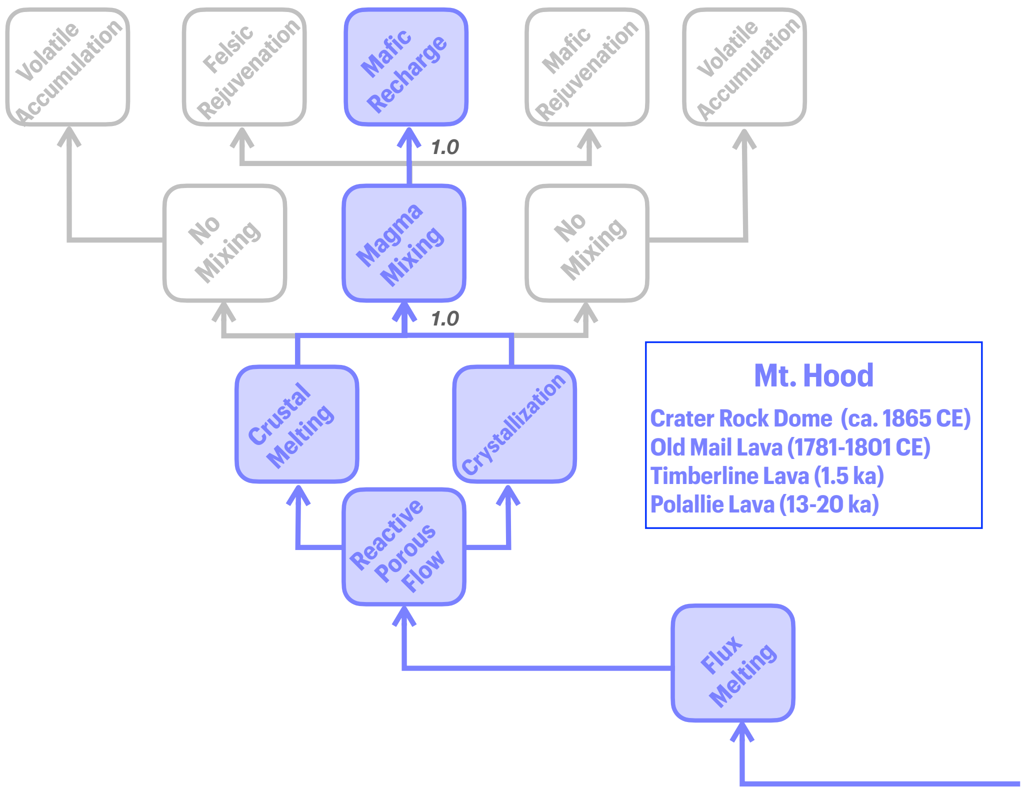


Figure 8: Magmatic tree for the last ~20 ka of activity at Mt. Hood, where all eruptions produced similar compositions of andesitic lava and are interpreted to have been caused by the same series of magmatic processes [Koleszar et al. 2012]. Gray numbers denote the probability of magma mixing and mafic recharge being involved in generating the erupted material during this time period, which is equal to 1.0 as all erupted magmas experienced these processes.

the US National Academies Decadal Report on Earth Sciences [2020].

Crust- and mantle-focused event trees can also contribute to conceptual models used for expert elicitation, data integration, and identification of analog systems in volcanic hazard assessments. However, these magmatic event trees fall short as a standalone tool for forecasting volcanic hazards. This is because we lack knowledge of how many times the same processes occurred at each volcano without culminating in an eruption. To be useful for hazard forecasting, event trees focused on mantle and crustal processes will need to be integrated with more traditional volcanic hazard event trees, which focus on behavior in the shallow sub-surface and draw on additional data types and histories of similar systems to better assess the probability that renewed activity will lead to an eruption (e.g. Figure 2A).

### 3.4 Magmatic trees and teaching

Magmatic trees can also be a useful framework to teach igneous processes. Providing frameworks such as this as a form of scaffolding has been found to increase student engagement in mathematics classrooms [Marshman and Brown 2014; Bakker et al. 2015], improve student's logical thinking ability in virtual classrooms [Noer Hodijah et al. 2018], and teach physics concepts to future physics teachers [Sinaga et al. 2015], as well as help students to understand a problem, develop hypotheses, ask more specific questions, and grasp multiple perspectives in an eighth grade science class [Zydney 2005]. Furthermore, meta-analysis suggests that problem-solving based instruction coupled with scaffolding is one of the most effective practices in STEM education [Belland 2017]. Thus, instruction that requires students to construct magmatic trees using a step-by-step process, computer-based or otherwise, is likely to prove effective to both teach content and higher-order critical thinking [Belland 2017].

A suggested teaching approach would be to use a basic magmatic tree structure like that in Figure 3 to introduce the range of processes typically taught in an igneous petrology course over successive classes, starting in the mantle and working towards the processes that occur shortly before and during an eruption. In conjunction, hands-on classroom or lab activities can focus on teaching students to distinguish between the processes at a given level in the tree and the

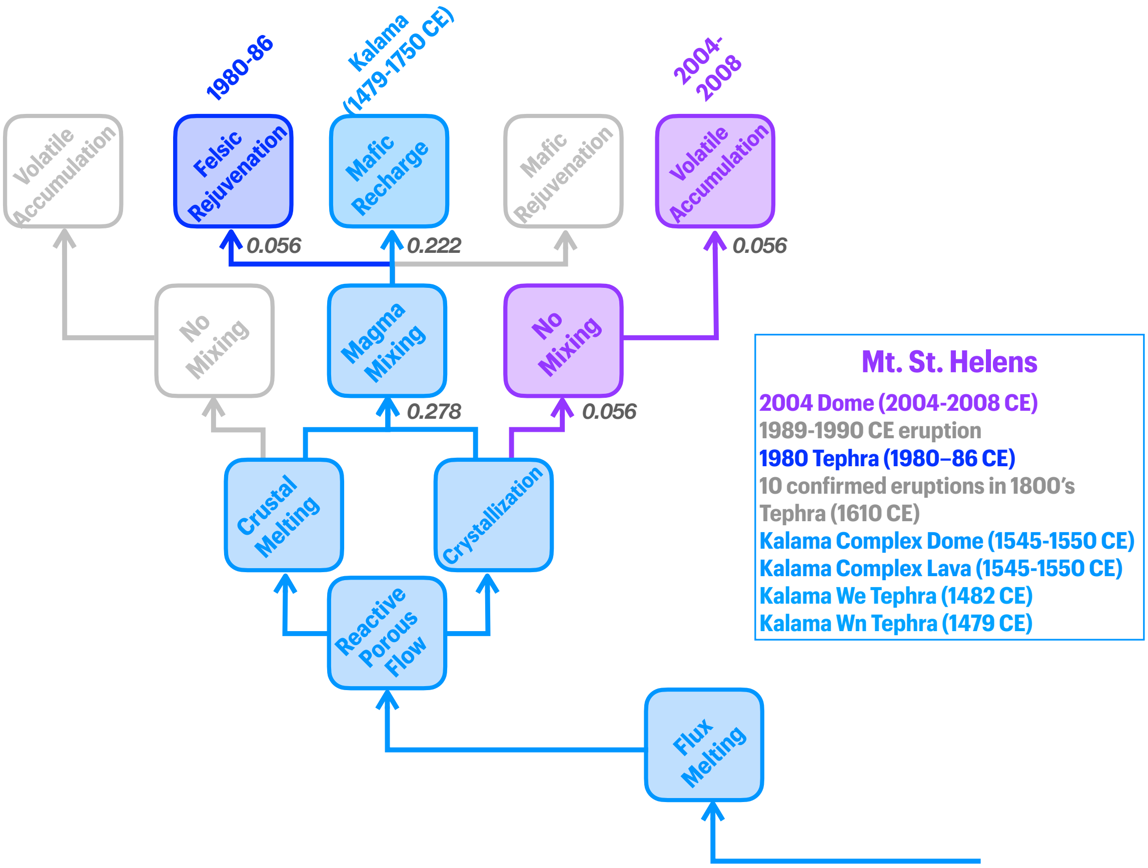


Figure 9: Magmatic tree for eruptions since 1480 CE at Mt. St. Helens with known eruption initiation mechanisms. Gray numbers denote the known probability of a particular process being involved in the generation of the 18 eruptions during this time period. Probabilities calculated as the number of instances of a process divided by the total number of eruptions (e.g. the 4 eruptions during the Kalama period out of the 18 total since 1480 CE are interpreted to have been initiated by mafic recharge, such that the probability of mafic recharge during this time period is 0.22). Because there are 12 eruptions with unknown initiation mechanisms, the probabilities at the top two levels do not total 1.0. Data from Carey et al. [1995], Gardner et al. [1995a,b], Kent et al. [2007], Pallister et al. [2008], Saunders et al. [2012], and Leeman and Smith [2018].

key evidence of each (e.g. the different characteristics of a basalt generated through flux versus decompression melting). After all the key igneous processes have been introduced, a capstone experience could include asking students to make a magmatic tree for a suite of samples from a particular eruption on their own. A step-by-step questionnaire for building magmatic trees, which is designed to be appropriate for students is included in Supplementary Material 1.

### 3.5 Other benefits and limitations

The list of benefits of constructing magmatic trees for igneous systems discussed thus far is by no means exhaustive. Magmatic trees also provide a way to understand the larger-scale conclusions of discipline-specific volcano studies (e.g. to relay the processes identified in a geochemical study to geophysicists interested in the same system) and communicate across disciplines. One is also forced to utilize a variety of data types to build a full tree from mantle origins to final emplacement, as no one data type is well suited to identifying all the igneous processes found in even the simplest tree, which reinforces interdisciplinary approaches to volcano science. In addition, magmatic trees provide a straightforward method to identify what information regarding a particular eruption or volcanic system is missing, survey the most critical holes in our understanding, and justify future work.

There are of course limitations to this graphical method. For example, in each tree there is equal weight given to each process identified and the trees do not emphasize the extent to which any one process is dominant in producing a given magma. If this is important for a given application, one could assign a weight to each process (for example from 0–1) and illustrate them on the tree, similar to what is done in Figure 4B. Trees also do not attempt to deal with the quantities involved in a given process, such as the mass, volume, or geochemical composition of the magma involved. While magmatic trees are designed to be primarily conceptual and focus on identifying processes, they could also easily work in a way where more mechanistic and quantitative models are plugged into a given process node on a tree. For example, tools such as `MELTS` or `Magma Chamber Simulator` could be used to model the silicate melt composition and equilibrium mineral phases during crystallization, or `VESIcal` could be used to model the accompanying fluid composition [e.g. Ghiorso and Sack 1995; Gualda et al. 2012; Bohrson et al. 2020; Heinonen et al. 2020; Iacovino et al. 2021; Wieser et al. 2022]. Similarly, thermo-mechanical models could be used to model the dynamics of processes on the tree, such as magma mixing leading to eruption [e.g. Degruyter and Huber 2014; Degruyter et al. 2016]. Additionally, physiochemical volcano models combined with remote sensing INSAR, thermal, and outgassing datasets could be used to model the fluxes involved in a recent or on-going mafic recharge or rejuvenation event [e.g. Anderson et al. 2019; Huber and Toramaru 2024]. Magmatic trees are not designed to focus on temporal constraints: while some processes may be entirely successive, many likely operate concurrently or overlap in time as can be illustrated in simple ways like in Figure 4A, which also illustrates ways to include geochronologic dates and rates on a tree where the necessary data is available. That said, trees are also designed to be useful even in the absence of geochronologic information. Finally, magmatic trees are constructed using interpretations, and not data exclusively, because of their emphasis on process. One could view this as a limitation because of the potential for error or bias in interpreting processes from data. Alternatively, this can be seen as a strength of the method, as constructing trees is excellent way to reveal or highlight discrepancies in interpretations and identify fundamental holes in our knowledge that can then be reconciled with future study.

## 4 Conclusions and future directions

At their simplest, magmatic trees provide a useful visualization to summarize the processes that formed a particular igneous rock. At their most sophisticated, magmatic trees provide a means to amalgamate decades of data on igneous processes to create models of volcanic systems and facilitate their comparison. The example applications discussed in Section 3 are just some of the ways in which a process-based graphical method like magmatic trees can help us to achieve our near- and mid-term community science goals [e.g. NASEM 2020; Brodsky et al. 2022].

One can imagine a near-term future where the Smithsonian's Global Volcanism Program website includes magmatic trees constructed for specific eruptions, including groups of trees that reveal differences in interpretations between studies, or partial trees that illustrate the gaps in our knowledge regarding past or on-going eruptions. Or alternatively, an online tool to manually construct magmatic trees could also host a library of trees that cite the literature and samples used to construct them.

Adopting process-based organizational methods also allows us to bypass some of the challenges faced in developing organizational schema in other scientific fields. Returning to the example of the development of phylogenetics discussed in the Introduction provides one instructional example. Recall, evolutionary biologists' use of exclusively data-driven clustering methods, like cladistics, starting in the early 1900s led to the conclusion that they created spurious groupings, especially for datasets comprised of a small number of independent characteristics for each sample. Over time, evolutionary biology and comparative linguistics discovered it was necessary to underpin organizational methods with known meaningful relationships, as is done in modern phylogenetics. Therefore, as we move into an era where artificial intelligence, large language models, and machines learning will play an increasing role in our science [e.g. Petrelli and Perugini 2016; Higgins et al. 2022; Petrelli 2024], training these data-driven tools with meaningful relationships and process-based frameworks, such as the one proposed here, will be increasingly important if they are to make consequential contributions to volcano science. For example, both supervised and unsupervised machine learning models could be used together to identify previously unrecognized patterns of magmatic behavior, with supervised models being trained to use geochemical data from past eruptions to identify underlying magmatic processes, such as crystallization and magma mixing, and unsupervised models using magmatic trees as inputs for hierarchical cluster analysis to identify common families or sequences of magmatic processes. Thus, one can imagine a future where machine learning removes much of the human error from magmatic process identification, as well as magmatic tree construction, further enhancing the utility of magmatic trees for event tree-type hazard forecasting and/or volcano classification.

In closing, at a minimum it is my hope that we can reinvigorate a conversation around how we compare and contrast igneous systems. Whether these conversations lead to embracing the use of magmatic trees or not, providing methods to summarize our existing knowledge of the mantle-to-surface magmatic processes contributing to a given eruption, or to examine the frequency of given process or sets of processes between volcanoes, will be a critical component of addressing questions like, "what drives volcanism?," one of the twelve priority science questions in the US National Academies Decadal Report on Earth Sciences [2020], as well as continuing to work towards findable, accessible, interoperable, and reusable (FAIR) data principles [Wilkinson et al. 2016].

## Author Contributions

C.B. Till conceived of this work, conducted the research, and prepared all text and figures.

## Acknowledgements

The idea for this paper started during my sabbatical at Oregon State University in Fall 2021 with a vibrant lunch conversation with Adam Kent, Andrea Goltz, Felix Ishimwe, and Jessica Bersson when snow thwarted our fieldwork plans at Santiam Pass, OR. Additional thanks to Matt Pritchard whose question during a conference presentation inspired the section on interpreting satellite data. I would also like to extend appreciation to Keith Putirka, Wendy Bohrson, and an anonymous reviewer for their thoughtful and constructive reviews of the manuscript, and Volcanica editor Jamie Farquharson for their editorial handling.

## Data Availability

All data utilized in this paper has been previously published in the cited references.

## Copyright notice



## References


Allison, C. M., K. Roggensack, and A. B. Clarke (2021). "Highly explosive basaltic eruptions driven by CO2 exsolution". *Nature Communications* 12(1), page 217. doi: 10.1038/s41467-020-20354-2.

Andersen, N. L., B. S. Singer, F. Costa, J. Fournelle, J. S. Herrin, and G. N. Fabbro (2018). "Petrochronologic perspective on rhyolite volcano unrest at Laguna del Maule, Chile". *Earth and Planetary Science Letters* 483, pages 57–70. doi: 10.1016/j.epsl.2018.03.043.

Anderson, K. R., I. A. Johanson, M. R. Patrick, M. Gu, P. Segall, M. P. Poland, E. K. Montgomery-Brown, and A. Miklius (2019). "Magma reservoir failure and the onset of caldera collapse at Kīlauea Volcano in 2018". *Science* 366(6470). doi: 10.1126/science.aaz1822.

Annen, C., J. D. Blundyy, and R. S. J. Sparks (2006). "The Genesis of Intermediate and Silicic Magmas in Deep Crustal Hot Zones". *Journal of Petrology* 47(3), pages 505–539. doi: 10.1093/petrology/egi084.

Arzilli, F., D. Morgavi, M. Petrelli, M. Polacci, M. Burton, D. Di Genova, L. Spina, G. La Spina, M. E. Hartley, J. E. Romero, J. Fellowes, J. Diaz-Alvarado, and D. Perugini (2019). "The unexpected explosive sub-Plinian eruption of Calbuco volcano (22–23 April 2015; southern Chile): Triggering mechanism implications". *Journal of Volcanology and Geothermal Research* 378, pages 35–50. doi: 10.1016/j.jvolgeores.2019.04.006.

Aspinall, W. P. and R. M. Cooke (1998). "Expert Judgement and the Montserrat Volcano Eruption". *Proceedings of the 4th International Conference on Probabilistic Safety Assessment and Management.* Edited by A. Mosleh and R. A. Bari. Volume 3. Springer, pages 2113–2118. isbn: 978-3540762621.

Aspinall, W. P. and G. Woo (2014). "Santorini unrest 2011–2012: an immediate Bayesian belief network analysis of eruption scenario probabilities for urgent decision support under uncertainty". *Journal of Applied Volcanology* 3(1). doi: 10.1186/s13617-014-0012-8.

Bachmann, O. and G. W. Bergantz (2008). "Rhyolites and their Source Mushes across Tectonic Settings". *Journal of Petrology* 49(12), pages 2277–2285. doi: 10.1093/petrology/egn068.

Bacon, C. R. (1986). "Magmatic inclusions in silicic and intermediate volcanic rocks". *Journal of Geophysical Research: Solid Earth* 91(B6), pages 6091–6112. doi: 10.1029/jb091ib06p06091.

Bacon, C. R. and T. H. Druitt (1988). "Compositional evolution of the zoned calcalkaline magma chamber of Mount Mazama, Crater Lake, Oregon". *Contributions to Mineralogy and Petrology* 98(2), pages 224–256. doi: 10.1007/bf00402114.

Bakker, A., J. Smit, and R. Wegerif (2015). "Scaffolding and dialogic teaching in mathematics education: introduction and review". *ZDM* 47(7), pages 1047–1065. doi: 10.1007/s11858-015-0738-8.

Belland, B. R. (2017). *Instructional Scaffolding in STEM Education*. Springer International Publishing. isbn: 9783319025650. doi: 10.1007/978-3-319-02565-0.

Bindeman, I. N., B. Fu, N. T. Kita, and J. W. Valley (2008). "Origin and Evolution of Silicic Magmatism at Yellowstone Based on Ion Microprobe Analysis of Isotopically Zoned Zircons". *Journal of Petrology* 49(1), pages 163–193. doi: 10.1093/petrology/egm075.

Blatter, D. L., T. W. Sisson, and W. B. Hankins (2013). "Crystallization of oxidized, moderately hydrous arc basalt at mid- to lower-crustal pressures: implications for andesite genesis". *Contributions to Mineralogy and Petrology* 166(3), pages 861–886. doi: 10.1007/s00410-013-0920-3.

– (2017). "Voluminous arc dacites as amphibole reaction-boundary liquids". *Contributions to Mineralogy and Petrology* 172(5). doi: 10.1007/s00410-017-1340-6.

Bohrson, W. A., F. J. Spera, M. S. Ghiorso, G. A. Brown, J. B. Creamer, and A. Mayfield (2014). "Thermodynamic Model for Energy-Constrained Open-System Evolution of Crustal Magma Bodies Undergoing Simultaneous Recharge, Assimilation and Crystallization: the Magma Chamber Simulator". *Journal of Petrology* 55(9), pages 1685–1717. doi: 10.1093/petrology/egu036.

Bohrson, W. A., F. J. Spera, J. S. Heinonen, G. A. Brown, M. A. Scruggs, J. V. Adams, M. K. Takach, G. Zeff, and E. Suikkanen (2020). "Diagnosing open-system magmatic processes using the Magma Chamber Simulator (MCS): part I—major elements and phase equilibria". *Contributions to Mineralogy and Petrology* 175(11). doi: 10.1007/s00410-020-01722-z.

Bouilhol, P., M. W. Schmidt, and J.-P. Burg (2015). "Magma Transfer and Evolution in Channels within the Arc Crust: the Pyroxenitic Feeder Pipes of Sapat (Kohistan, Pakistan)". *Journal of Petrology* 56(7), pages 1309–1342. doi: 10.1093/petrology/egv037.

Bowen, N. L. (1928). *The evolution of the igneous rocks*. Princeton: Princeton University Press. 334 pages.

Brandmeier, M. and G. Wörner (2016). "Compositional variations of ignimbrite magmas in the Central Andes over the past 26 Ma — A multivariate statistical perspective". *Lithos* 262, pages 713–728. doi: 10.1016/j.lithos.2016.07.011.

Brodsky, E. E., D. Roman, D. J. Shillington, M. Brudzinski, M. Behn, H. Tobin, and the SZ4D RCN (2022). "SZ4D Implementation Plan". *Stanford Digital Repository*. Edited by G. Hilley. DOI: 10.25740/HY589FC7561.

Brower, A. V. Z. (2000). "Evolution Is Not a Necessary Assumption of Cladistics". *Cladistics* 16(1), pages 143–154. DOI: 10.1111/j.1096-0031.2000.tb00351.x.

Brower, A. V. Z. and R. T. Schuh (2021). *Biological systematics: principles and applications*. 3rd edition. Ithica: Cornell University Press.

Cabaniss, H. E., P. M. Gregg, and E. B. Grosfils (2018). "The Role of Tectonic Stress in Triggering Large Silicic Caldera Eruptions". *Geophysical Research Letters* 45(9), pages 3889–3895. DOI: 10.1029/2018gl077393.

Carey, S., J. E. Gardner, and H. Sigurdsson (1995). "The intensity and magnitude of Holocene plinian eruptions from Mount St. Helens volcano". *Journal of Volcanology and Geothermal Research* 66(1–4), pages 185–202. DOI: 10.1016/0377-0273(94)00059-p.

Caricchi, L., C. Annen, J. Blundy, G. Simpson, and V. Pinel (2014). "Frequency and magnitude of volcanic eruptions controlled by magma injection and buoyancy". *Nature Geoscience* 7(2), pages 126–130. DOI: 10.1038/ngeo2041.

Caricchi, L., M. Townsend, E. Rivalta, and A. Namiki (2021). "The build-up and triggers of volcanic eruptions". *Nature Reviews Earth & Environment* 2(7), pages 458–476. DOI: 10.1038/s43017-021-00174-8.

Cashman, K. and J. Biggs (2014). "Common processes at unique volcanoes—a volcanological conundrum". *Frontiers in Earth Science* 2. DOI: 10.3389/feart.2014.00028.

Cassidy, M., M. Manga, K. Cashman, and O. Bachmann (2018). "Controls on explosive-effusive volcanic eruption styles". *Nature Communications* 9(1). DOI: 10.1038/s41467-018-05293-3.

Castruccio, A., J. Clavero, A. Segura, P. Samaniego, O. Roche, J.-L. Le Pennec, and B. Droguett (2016). "Eruptive parameters and dynamics of the April 2015 sub-Plinian eruptions of Calbuco volcano (southern Chile)". *Bulletin of Volcanology* 78(9). DOI: 10.1007/s00445-016-1058-8.

Cattell, R. B. (1943). "The description of personality: basic traits resolved into clusters." *The Journal of Abnormal and Social Psychology* 38(4), pages 476–506. DOI: 10.1037/h0054116.

Cerpa, N. G., I. Wada, and C. R. Wilson (2018). "Effects of fluid influx, fluid viscosity, and fluid density on fluid migration in the mantle wedge and their implications for hydrous melting". *Geosphere* 15(1), pages 1–23. DOI: 10.1130/ges01660.1.

Christophersen, A., N. I. Deligne, A. M. Hanea, L. Chardot, N. Fournier, and W. P. Aspinall (2018). "Bayesian Network Modeling and Expert Elicitation for Probabilistic Eruption Forecasting: Pilot Study for Whakaari/White Island, New Zealand". *Frontiers in Earth Science* 6. DOI: 10.3389/feart.2018.00211.

Clynne, M. A. (1999). "A Complex Magma Mixing Origin for Rocks Erupted in 1915, Lassen Peak, California". *Journal of Petrology* 40(1), pages 105–132. DOI: 10.1093/petroj/40.1.105.

Cortés, J. A., J. L. Palma, and M. Wilson (2007). "Deciphering magma mixing: The application of cluster analysis to the mineral chemistry of crystal populations". *Journal of Volcanology and Geothermal Research* 165(3–4), pages 163–188. DOI: 10.1016/j.jvolgeores.2007.05.018.

Darwin, C. (1859). "On the imperfection of the geological record". *On the origin of species by means of natural selection: Or the preservation of the favoured races in the struggle for life*. London: John Murray, pages 279–311. DOI: 10.1037/14088-009.

Degruyter, W. and C. Huber (2014). "A model for eruption frequency of upper crustal silicic magma chambers". *Earth and Planetary Science Letters* 403, pages 117–130. DOI: 10.1016/j.epsl.2014.06.047.

Degruyter, W., C. Huber, O. Bachmann, K. M. Cooper, and A. J. R. Kent (2016). "Magma reservoir response to transient recharge events: The case of Santorini volcano (Greece)". *Geology* 44(1), pages 23–26. DOI: 10.1130/g37333.1.

Delph, J. R., K. Shimizu, and B. C. Ratschbacher (2021). "The Architecture of the Southern Puna Magmatic System: Integrating Seismic and Petrologic Observations With Geochemical Modeling". *Journal of Geophysical Research: Solid Earth* 126(7). DOI: 10.1029/2020jb021550.

De Silva, S., J. Roberge, L. Bardelli, W. Báez, A. Ortiz, J. Viramonte, J. Arnosio, and R. Becchio (2022). "Magmatic evolution and architecture of an arc-related, rhyolitic caldera complex: The late Pleistocene to Holocene Cerro Blanco volcanic complex, southern Puna, Argentina". *Geosphere* 18(2), pages 394–423. DOI: 10.1130/ges02294.1.

Di Muro, A., J. Pallister, B. Villemant, C. G. Newhall, M. Semet, M. Martinez, and C. Mariet (2008). "Pre-1991 sulfur transfer between mafic injections and dacite magma in the Mt. Pinatubo reservoir". *Journal of Volcanology and Geothermal Research* 175(4), pages 517–540. DOI: 10.1016/j.jvolgeores.2008.02.025.

Driver, H. E. and A. L. Kroeber (1932). *Quantitative expression of cultural relationships*. Volume 31. 4. Berkeley: University of California Press. 256 pages.

Dufek, J. and G. W. Bergantz (2005). "Lower Crustal Magma Genesis and Preservation: a Stochastic Framework for the Evaluation of Basalt–Crust Interaction". *Journal of Petrology* 46(11), pages 2167–2195. DOI: 10.1093/petrology/egi049.

Eichelberger, J. C., C. R. Carrigan, H. R. Westrich, and R. H. Price (1986). "Non-explosive silicic volcanism". *Nature* 323(6089), pages 598–602. DOI: 10.1038/323598a0.

Eichelberger, J. C., P. E. Izbekov, and B. L. Browne (2006). "Bulk chemical trends at arc volcanoes are not liquid lines of descent". *Lithos* 87(1–2), pages 135–154. DOI: 10.1016/j.lithos.2005.05.006.

Feeley, T. C., M. A. Clynne, G. S. Winer, and W. C. Grice (2008). "Oxygen Isotope Geochemistry of the Lassen Volcanic Center, California: Resolving Crustal and Mantle Contributions to Continental Arc Magmatism". *Journal of Petrology* 49(5), pages 971–997. DOI: 10.1093/petrology/egn013.

Fowler, S. J. and F. J. Spera (2008). "Phase equilibria trigger for explosive volcanic eruptions". *Geophysical Research Letters* 35(8). DOI: 10.1029/2008gl033665.

– (2010). "A Metamodel for Crustal Magmatism: Phase Equilibria of Giant Ignimbrites". *Journal of Petrology* 51(9), pages 1783–1830. DOI: 10.1093/petrology/egq039.

Gaetani, G. A. and T. L. Grove (1998). "The influence of water on melting of mantle peridotite". *Contributions to Mineralogy and Petrology* 131(4), pages 323–346. DOI: 10.1007/s004100050396.

Gardner, J. E., S. Carey, M. J. Rutherford, and H. Sigurdsson (1995a). "Petrologic diversity in Mount St. Helens dacites during the last 4, 000 years: implications for magma mixing". *Contributions to Mineralogy and Petrology* 119(2–3), pages 224–238. DOI: 10.1007/bf00307283.

Gardner, J. E., M. Rutherford, S. Carey, and H. Sigurdsson (1995b). "Experimental constraints on pre-eruptive water contents and changing magma storage prior to explosive eruptions of Mount St Helens volcano". *Bulletin of Volcanology* 57(1), pages 1–17. DOI: 10.1007/bf00298703.

Geist, D. J., G. Bergantz, and W. W. Chadwick (2014). "Galápagos Magma Chambers". *The Galápagos: A Natural Laboratory for the Earth Sciences*. Edited by K. S. Harpp, E. Mittelstaedt, N. d'Ozouville, and D. W. Graham. Hoboken: John Wiley & Sons, Inc.; American Geophysical Union. Chapter 5, pages 55–69. ISBN: 9781118852538. DOI: 10.1002/9781118852538.ch5.

Geist, D. J., K. A. Howard, and P. Larson (1995). "The Generation of Oceanic Rhyolites by Crystal Fractionation: the Basalt-Rhyolite Association at Volcán Alcedo, Galápagos Archipelago". *Journal of Petrology* 36(4), pages 965–982. DOI: 10.1093/petrology/36.4.965.

Ghiorso, M. S. and R. O. Sack (1995). "Chemical mass transfer in magmatic processes IV. A revised and internally consistent thermodynamic model for the interpolation and extrapolation of liquid-solid equilibria in magmatic systems at elevated temperatures and pressures". *Contributions to Mineralogy and Petrology* 119(2–3), pages 197–212. DOI: 10.1007/bf00307281.

Gregg, P., S. de Silva, E. Grosfils, and J. Parmigiani (2012). "Catastrophic caldera-forming eruptions: Thermomechanics and implications for eruption triggering and maximum caldera dimensions on Earth". *Journal of Volcanology and Geothermal Research* 241–242, pages 1–12. DOI: 10.1016/j.jvolgeores.2012.06.009.

Grove, T. L. and M. B. Baker (1984). "Phase equilibrium controls on the tholeiitic versus calc-alkaline differentiation trends". *Journal of Geophysical Research: Solid Earth* 89(B5), pages 3253–3274. DOI: 10.1029/jb089ib05p03253.

Grove, T. L., N. Chatterjee, S. Parman, and E. Médard (2006). "The influence of H2O on mantle wedge melting". *Earth and Planetary Science Letters* 249(1–2), pages 74–89. DOI: 10.1016/j.epsl.2006.06.043.

Grove, T. L., L. T. Elkins-Tanton, S. W. Parman, N. Chatterjee, O. Müntener, and G. A. Gaetani (2003). "Fractional crystallization and mantle-melting controls on calc-alkaline differentiation trends". *Contributions to Mineralogy and Petrology* 145(5), pages 515–533. DOI: 10.1007/s00410-003-0448-z.

Grove, T. L., S. Parman, S. Bowring, R. Price, and M. Baker (2002). "The role of an H2O-rich fluid component in the generation of primitive basaltic andesites and andesites from the Mt. Shasta region, N California". *Contributions to Mineralogy and Petrology* 142(4), pages 375–396. DOI: 10.1007/s004100100299.

Grove, T. L. and C. B. Till (2015). "Melting the Earth's Upper Mantle". *The Encyclopedia of Volcanoes*. Edited by H. Sigurdsson, B. Houghton, S. McNutt, H. Rymer, and J. Stix. 2nd edition. Elsevier, pages 35–47. ISBN: 9780123859389. DOI: 10.1016/b978-0-12-385938-9.00001-8.

– (2019). "H2O-rich mantle melting near the slab–wedge interface". *Contributions to Mineralogy and Petrology* 174(10). DOI: 10.1007/s00410-019-1615-1.

Grove, T. L., C. B. Till, and M. J. Krawczynski (2012). "The Role of H2O in Subduction Zone Magmatism". *Annual Review of Earth and Planetary Sciences* 40(1), pages 413–439. DOI: 10.1146/annurev-earth-042711-105310.

Gualda, G. A. R., M. S. Ghiorso, R. V. Lemons, and T. L. Carley (2012). "Rhyolite-MELTS: a Modified Calibration of MELTS Optimized for Silica-rich, Fluid-bearing Magmatic Systems". *Journal of Petrology* 53(5), pages 875–890. DOI: 10.1093/petrology/egr080.

Hamada, M. and T. Fujii (2008). "Experimental constraints on the effects of pressure and H2O on the fractional crystallization of high-Mg island arc basalt". *Contributions to Mineralogy and Petrology* 155(6), pages 767–790. DOI: 10.1007/s00410-007-0269-6.

Hamling, I. J. and G. Kilgour (2020). "Goldilocks conditions required for earthquakes to trigger basaltic eruptions: Evidence from the 2015 Ambrym eruption". *Science Advances* 6(14). DOI: 10.1126/sciadv.aaz5261.

Harpp, K. S. and W. M. White (2001). "Tracing a mantle plume: Isotopic and trace element variations of Galápagos seamounts". *Geochemistry, Geophysics, Geosystems* 2(6). DOI: 10.1029/2000gc000137.

Harris, D. M. and A. T. Anderson (1984). "Volatiles H2O, CO2, and Cl in a subduction related basalt". *Contributions to Mineralogy and Petrology* 87(2), pages 120–128. DOI: 10.1007/bf00376218.

Heinonen, J. S., W. A. Bohrson, F. J. Spera, G. A. Brown, M. A. Scruggs, and J. V. Adams (2020). "Diagnosing open-system magmatic processes using the Magma Chamber Simulator (MCS): part II—trace elements and isotopes". *Contributions to Mineralogy and Petrology* 175(11). DOI: 10.1007/s00410-020-01718-9.

Hennig, W. (1965). "Phylogenetic Systematics". *Annual Review of Entomology* 10(1), pages 97–116. DOI: 10.1146/annurev.en.10.010165.000525.

Hidalgo, S., J. Battaglia, S. Arellano, D. Sierra, B. Bernard, R. Parra, P. Kelly, F. Dinger, C. Barrington, and P. Samaniego (2018). "Evolution of the 2015 Cotopaxi Eruption Revealed by Combined Geochemical and Seismic Observations". *Geochemistry, Geophysics, Geosystems* 19(7), pages 2087–2108. DOI: 10.1029/2018gc007514.

Higgins, O., T. Sheldrake, and L. Caricchi (2022). "Machine learning thermobarometry and chemometry using amphibole and clinopyroxene: a window into the roots of an arc volcano (Mount Liamuiga, Saint Kitts)". *Contributions to*

*Mineralogy and Petrology* 177(1). DOI: 10.1007/s00410-021-01874-6.

Hincks, T. K., J.-C. Komorowski, S. R. Sparks, and W. P. Aspinall (2014). "Retrospective analysis of uncertain eruption precursors at La Soufrière volcano, Guadeloupe, 1975–77: volcanic hazard assessment using a Bayesian Belief Network approach". *Journal of Applied Volcanology* 3(1). DOI: 10.1186/2191-5040-3-3.

Hoenigswald, H. M. (1960). *Language change and linguistic reconstruction*. Chicago: University of Chicago Press. 168 pages.

Hone, D. W. E., S. H. Mahony, R. S. J. Sparks, and K. T. Martin (2007). "Cladistic analysis applied to the classification of volcanoes". *Bulletin of Volcanology* 70(2), pages 203–220. DOI: 10.1007/s00445-007-0132-7.

Huber, C. and A. Toramaru (2024). "Increase in magma supply to Sakurajima volcano's (Japan) shallow magma chamber over the past 500 years". *Geology* 52(4), pages 235–239. DOI: 10.1130/g51763.1.

Huber, C., M. Townsend, W. Degruyter, and O. Bachmann (2019). "Optimal depth of subvolcanic magma chamber growth controlled by volatiles and crust rheology". *Nature Geoscience* 12(9), pages 762–768. DOI: 10.1038/s41561-019-0415-6.

Humphreys, M. C. S., T. Christopher, and V. Hards (2009). "Microlite transfer by disaggregation of mafic inclusions following magma mixing at Soufrière Hills volcano, Montserrat". *Contributions to Mineralogy and Petrology* 157(5), pages 609–624. DOI: 10.1007/s00410-008-0356-3.

Iacovino, K., S. Matthews, P. E. Wieser, G. M. Moore, and F. Bégué (2021). "VESIcal Part I: An Open-Source Thermodynamic Model Engine for Mixed Volatile (H2O-CO2) Solubility in Silicate Melts". *Earth and Space Science* 8(11). DOI: 10.1029/2020ea001584.

Jagoutz, O., O. Müntener, M. W. Schmidt, and J.-P. Burg (2011). "The roles of flux- and decompression melting and their respective fractionation lines for continental crust formation: Evidence from the Kohistan arc". *Earth and Planetary Science Letters* 303(1–2), pages 25–36. DOI: 10.1016/j.epsl.2010.12.017.

Jaupart, C. and C. J. Allègre (1991). "Gas content, eruption rate and instabilities of eruption regime in silicic volcanoes". *Earth and Planetary Science Letters* 102(3–4), pages 413–429. DOI: 10.1016/0012-821x(91)90032-d.

Juster, T. C., T. L. Grove, and M. R. Perfit (1989). "Experimental constraints on the generation of FeTi basalts, andesites, and rhyodacites at the Galapagos Spreading Center, 85°W and 95°W". *Journal of Geophysical Research: Solid Earth* 94(B7), pages 9251–9274. DOI: 10.1029/jb094ib07p09251.

Karakas, O. and J. Dufek (2015). "Melt evolution and residence in extending crust: Thermal modeling of the crust and crustal magmas". *Earth and Planetary Science Letters* 425, pages 131–144. DOI: 10.1016/j.epsl.2015.06.001.

Katz, R. F., D. W. R. Jones, J. F. Rudge, and T. Keller (2022). "Physics of Melt Extraction from the Mantle: Speed and Style". *Annual Review of Earth and Planetary Sciences* 50(1), pages 507–540. DOI: 10.1146/annurev-earth-032320-083704.

Kayzar, T. M., K. M. Cooper, M. K. Reagan, and A. J. Kent (2009). "Gas transport model for the magmatic system at Mount Pinatubo, Philippines: Insights from (210Pb)/(226Ra)". *Journal of Volcanology and Geothermal Research* 181(1–2), pages 124–140. DOI: 10.1016/j.jvolgeores.2009.01.006.

Kent, A. J. R., J. Blundy, K. V. Cashman, K. M. Cooper, C. Donnelly, J. S. Pallister, M. Reagan, M. C. Rowe, and C. R. Thornber (2007). "Vapor transfer prior to the October 2004 eruption of Mount St. Helens, Washington". *Geology* 35(3), page 231. DOI: 10.1130/g22809a.1.

Kent, A. J. R., C. Darr, A. M. Koleszar, M. J. Salisbury, and K. M. Cooper (2010). "Preferential eruption of andesitic magmas through recharge filtering". *Nature Geoscience* 3(9), pages 631–636. DOI: 10.1038/ngeo924.

Kent, A. J. R., C. B. Till, and K. M. Cooper (2023). "Start me up: The relationship between volcanic eruption characteristics and eruption initiation mechanisms". *Volcanica* 6(2), pages 161–172. DOI: 10.30909/vol.06.02.161172.

Koleszar, A. M., A. J. Kent, P. J. Wallace, and W. E. Scott (2012). "Controls on long-term low explosivity at andesitic arc volcanoes: Insights from Mount Hood, Oregon". *Journal of Volcanology and Geothermal Research* 219–220, pages 1–14. DOI: 10.1016/j.jvolgeores.2012.01.003.

Kousky, C. and R. M. Cooke (2012). "The Value of Information in a Risk Management Approach to Climate Change". *The Value of Information*. Springer Netherlands, pages 19–43. ISBN: 9789400748392. DOI: 10.1007/978-94-007-4839-2_2.

Krawczynski, M. J., T. L. Grove, and H. Behrens (2012). "Amphibole stability in primitive arc magmas: effects of temperature, H2O content, and oxygen fugacity". *Contributions to Mineralogy and Petrology* 164(2), pages 317–339. DOI: 10.1007/s00410-012-0740-x.

Krein, S. B., M. D. Behn, and T. L. Grove (2021). "Origins of Major Element, Trace Element, and Isotope Garnet Signatures in Mid-Ocean Ridge Basalts". *Journal of Geophysical Research: Solid Earth* 125(12). DOI: 10.1029/2020jb019612.

Leeman, W. P. and D. R. Smith (2018). "The role of magma mixing, identification of mafic magma inputs, and structure of the underlying magmatic system at Mount St. Helens". *American Mineralogist* 103(12), pages 1925–1944. DOI: 10.2138/am-2018-6555.

Liu, E. J., K. V. Cashman, E. Miller, H. Moore, M. Edmonds, B. E. Kunz, F. Jenner, and G. Chigna (2020). "Petrologic monitoring at Volcán de Fuego, Guatemala". *Journal of Volcanology and Geothermal Research* 405, page 107044. DOI: 10.1016/j.jvolgeores.2020.107044.

Malfait, W. J., R. Seifert, S. Petitgirard, J.-P. Perrillat, M. Mezouar, T. Ota, E. Nakamura, P. Lerch, and C. Sanchez-Valle (2014). "Supervolcano eruptions driven by melt buoyancy in large silicic magma chambers". *Nature Geoscience* 7(2), pages 122–125. DOI: 10.1038/ngeo2042.

Marsh, B. D. (1984). "Mechanics and energetics of magma formation and ascension". *Explosive volcanism: inception, evolution, and hazards*. Edited by F. Boyd Jr. Studies in Geophysics. Washington, D.C.: National Academy Press, pages 67–83.

Marshman, M. and R. Brown (2014). "Coming to Know and Do Mathematics with Disengaged Students." *Mathematics Teacher Education and Development* 16(2), pages 71–88.

Marxer, F., P. Ulmer, and O. Müntener (2023). "Ascent-driven differentiation: a mechanism to keep arc magmas metaluminous?" *Contributions to Mineralogy and Petrology* 178(8). DOI: 10.1007/s00410-023-02035-7.

Mitchell, A. L. and T. L. Grove (2015). "Melting the hydrous, subarc mantle: the origin of primitive andesites". *Contributions to Mineralogy and Petrology* 170(2). DOI: 10.1007/s00410-015-1161-4.

– (2016). "Experiments on melt–rock reaction in the shallow mantle wedge". *Contributions to Mineralogy and Petrology* 171(12). DOI: 10.1007/s00410-016-1312-2.

Morgado, E., D. J. Morgan, A. Castruccio, S. K. Ebmeier, M.-Á. Parada, R. Brahm, J. Harvey, F. Gutiérrez, and R. Walshaw (2019). "Old magma and a new, intrusive trigger: using diffusion chronometry to understand the rapid-onset Calbuco eruption, April 2015 (Southern Chile)". *Contributions to Mineralogy and Petrology* 174(7). DOI: 10.1007/s00410-019-1596-0.

Muir, D. D., J. D. Blundy, M. C. Hutchinson, and A. C. Rust (2014a). "Petrological imaging of an active pluton beneath Cerro Uturuncu, Bolivia". *Contributions to Mineralogy and Petrology* 167(3). DOI: 10.1007/s00410-014-0980-z.

Muir, D. D., J. D. Blundy, A. C. Rust, and J. Hickey (2014b). "Experimental Constraints on Dacite Pre-eruptive Magma Storage Conditions beneath Uturuncu Volcano". *Journal of Petrology* 55(4), pages 749–767. DOI: 10.1093/petrology/egu005.

Mutch, E. J. F., J. Maclennan, O. Shorttle, M. Edmonds, and J. F. Rudge (2019). "Rapid transcrustal magma movement under Iceland". *Nature Geoscience* 12(7), pages 569–574. DOI: 10.1038/s41561-019-0376-9.

Namur, O., S. Montalbano, O. Bolle, and J. Vander Auwera (2020). "Petrology of the April 2015 Eruption of Calbuco Volcano, Southern Chile". *Journal of Petrology* 61(8). DOI: 10.1093/petrology/egaa084.

National Academies of Sciences, Engineering and Medicine (NASEM) (2017). *Volcanic Eruptions and Their Repose, Unrest, Precursors, and Timing*. Washington, D.C.: National Academies Press. 134 pages. ISBN: 9780309454124. DOI: 10.17226/24650.

– (2020). *A Vision for NSF Earth Sciences 2020-2030: Earth in Time*. Washington, D.C.: National Academies Press. ISBN: 9780309676007. DOI: 10.17226/25761.

Neil, M., N. Fenton, and M. Tailor (2005). "Using Bayesian Networks to Model Expected and Unexpected Operational Losses". *Risk Analysis* 25(4), pages 963–972. DOI: 10.1111/j.1539-6924.2005.00641.x.

Newhall, C. G. (1982). *A method for estimating intermediate and long-term risks from volcanic activity, with an example from Mount St. Helens, Washington*. DOI: 10.3133/ofr82396.

– (1984). *Semiquantitative assessment of changing volcanic risk at Mount St. Helens, Washington*. DOI: 10.3133/ofr84272.

Newhall, C. G. and R. Hoblitt (2002). "Constructing event trees for volcanic crises". *Bulletin of Volcanology* 64(1), pages 3–20. DOI: 10.1007/s004450100173.

Noer Hodijah, S. R., R. Sudiana, and D. Murni (2018). "The Effectiveness of Scaffolding Based Virtual Class to Improve Student's Logical Thinking Ability". *Jurnal Penelitian dan Pembelajaran IPA* 4(1), page 51. DOI: 10.30870/jppi.v4i1.3041.

Pallister, J. S., C. R. Thornber, K. V. Cashman, M. A. Clynne, H. A. Lowers, C. W. Mandeville, I. K. Brownfield, G. P. Meeker, D. Sherrod, W. Scott, et al. (2008). "Petrology of the 2004–2006 Mount St. Helens lava dome—implications for magmatic plumbing and eruption triggering". *A Volcano Rekindled: The Renewed Eruption of Mount St. Helens, 2004–2006*. Edited by D. R. Sherrod, W. E. Scott, and P. H. Stauffer. Reston, Virginia: U.S. Geological Survey, pages 647–702. U.S. Geological Survey Professional paper 1750.

Pallister, J. S., R. P. Hoblitt, and A. G. Reyes (1992). "A basalt trigger for the 1991 eruptions of Pinatubo volcano?" *Nature* 356(6368), pages 426–428. DOI: 10.1038/356426a0.

Pearson, K. (1901). "LIII. On lines and planes of closest fit to systems of points in space". *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 2(11), pages 559–572. DOI: 10.1080/14786440109462720.

Petrelli, M. (2024). "Machine Learning in Petrology: State-of-the-Art and Future Perspectives". *Journal of Petrology* 65(5). DOI: 10.1093/petrology/egae036.

Petrelli, M. and D. Perugini (2016). "Solving petrological problems through machine learning: the study case of tectonic discrimination using geochemical and isotopic data". *Contributions to Mineralogy and Petrology* 171(10). DOI: 10.1007/s00410-016-1292-2.

Phillips, M. and C. B. Till (2022). "Crustal storage and ascent history of the Mt. Shasta primitive magnesian andesite: implications for arc magma crustal flux rates". *Contributions to Mineralogy and Petrology* 177(1). DOI: 10.1007/s00410-021-01853-x.

Pitcher, B. W. and A. J. Kent (2019). "Statistics and segmentation: Using Big Data to assess Cascades arc compositional variability". *Geochimica et Cosmochimica Acta* 265, pages 443–467. DOI: 10.1016/j.gca.2019.08.035.

Platnick, N. I. and H. D. Cameron (1977). "Cladistic Methods in Textual, Linguistic, and Phylogenetic Analysis". *Systematic Zoology* 26(4), page 380. DOI: 10.2307/2412794.

Poland, M. P. and K. R. Anderson (2020). "Partly Cloudy With a Chance of Lava Flows: Forecasting Volcanic Eruptions in the Twenty-First Century". *Journal of Geophysical Research: Solid Earth* 125(1). DOI: 10.1029/2018jb016974.

Puga, J. L., M. Krzywinski, and N. Altman (2015). "Bayesian networks". *Nature Methods* 12(9), pages 799–800. DOI: 10.1038/nmeth.3550.

Putirka, K. D., M. Perfit, F. Ryerson, and M. G. Jackson (2007). "Ambient and excess mantle temperatures, olivine thermometry, and active vs. passive upwelling". *Chemical Geology* 241(3–4), pages 177–206. DOI: 10.1016/j.chemgeo.2007.01.014.

Rasmussen, D. J., T. A. Plank, D. C. Roman, J. A. Power, R. J. Bodnar, and E. H. Hauri (2018). "When does eruption run-up begin? Multidisciplinary insight from the 1999 eruption of Shishaldin volcano". *Earth and Planetary Science Letters* 486, pages 1–14. DOI: 10.1016/j.epsl.2018.01.001.

Ratschbacher, B. C., K. Ardill, C. B. Keller, B. Schoene, S. R. Paterson, K. D. Putirka, J. S. Lackey, and M. L. Paige (2024). "Multi-scale, open-system magmatic and sub-solidus processes contribute to the chemical and isotopic characteristics of the Jurassic Guadalupe Igneous Complex, Sierra Nevada, California, USA". *Geosphere* 20(4), pages 1005–1029. DOI: 10.1130/ges02689.1.

Reath, K., M. Pritchard, J. Biggs, B. Andrews, S. K. Ebmeier, M. Bagnardi, T. Girona, P. Lundgren, T. Lopez, and M. Poland (2020). "Using Conceptual Models to Relate Multiparameter Satellite Data to Subsurface Volcanic Processes in Latin America". *Geochemistry, Geophysics, Geosystems* 21(1). DOI: 10.1029/2019gc008494.

Reath, K., M. Pritchard, M. Poland, F. Delgado, S. Carn, D. Coppola, B. Andrews, S. K. Ebmeier, E. Rumpf, S. Henderson, S. Baker, P. Lundgren, R. Wright, J. Biggs, T. Lopez, C. Wauthier, S. Moruzzi, A. Alcott, R. Wessels, J. Griswold, S. Ogburn, S. Loughlin, F. Meyer, G. Vaughan, and M. Bagnardi (2019). "Thermal, Deformation, and Degassing Remote Sensing Time Series (CE 2000–2017) at the 47 most Active Volcanoes in Latin America: Implications for Volcanic Systems". *Journal of Geophysical Research: Solid Earth* 124(1), pages 195–218. DOI: 10.1029/2018jb016199.

Rittmann, A. (1962). *Volcanoes and their activity*. Translated by E. A. Vincent. New York/ London: John Wiley & Sons: Interscience Publishers.

Ruprecht, P. and T. Plank (2013). "Feeding andesitic eruptions with a high-speed connection from the mantle". *Nature* 500(7460), pages 68–72. DOI: 10.1038/nature12342.

Rushmer, T. (1991). "Partial melting of two amphibolites: contrasting experimental results under fluid-absent conditions". *Contributions to Mineralogy and Petrology* 107(1), pages 41–59. DOI: 10.1007/bf00311184.

Ruth, D. C. S., E. Cottrell, J. A. Cortés, K. A. Kelley, and E. S. Calder (2016). "From Passive Degassing to Violent Strombolian Eruption: the Case of the 2008 Eruption of Llaima Volcano, Chile". *Journal of Petrology* 57 (9), pages 1833–1864. DOI: 10.1093/petrology/egw063.

Sack, R. O., D. Walker, and I. S. E. Carmichael (1987). "Experimental petrology of alkalic lavas: constraints on cotectics of multiple saturation in natural basic liquids". *Contributions to Mineralogy and Petrology* 96(1), pages 1–23. DOI: 10.1007/bf00375521.

Saunders, K., J. Blundy, R. Dohmen, and K. Cashman (2012). "Linking Petrology and Seismology at an Active Volcano". *Science* 336(6084), pages 1023–1027. DOI: 10.1126/science.1220066.

Scrope, G. P. (1872). *Uber Vulkane: Der Charakter ihrer Phänomene, ihre Rolle in dem Bau und in der Zusammensetzung der Erdoberfläche und ihre Beziehung zu den Kräften des Inneren; nebst einem beschreibenden Verzeichnisse aller bekannten Vulkane und vulkanischen Bildungen*. Berlin: Oppenheim. 473 pages.

Shamloo, H. I. and C. B. Till (2019). "Decadal transition from quiescence to supereruption: petrologic investigation of the Lava Creek Tuff, Yellowstone Caldera, WY". *Contributions to Mineralogy and Petrology* 174(4). DOI: 10.1007/s00410-019-1570-x.

Sigurdsson, H. (2000). "The history of volcanology". *Encyclopedia of Volcanoes*. Edited by H. Sigurdsson, B. Houghton, H. Rymer, J. Stix, and S. McNutt. 1st edition. San Diego: Academic Press, pages 15–37. ISBN: 9780080547985.

Simkin, T. and L. Siebert (1994). *Volcanoes of the world (2d ed.): Tucson, Ariz.* 2nd edition. Tucson: Geoscience Press, Inc., in association with the Smithsonian Institution. 349 pages. ISBN: 0 945005 12 1.

Sinaga, P., A. Suhandi, and L. - (2015). "The Effectiveness of Scaffolding Design in Training Writing Skills Physics Teaching Materials". *International Journal of Instruction* 8(1), pages 19–34. DOI: 10.12973/iji.2015.812a.

Sisson, T. W. and C. R. Bacon (1999). "Gas-driven filter pressing in magmas". *Geology* 27(7), page 613. DOI: 10.1130/0091-7613(1999)027<0613:gdfpim>2.3.co;2.

Sisson, T. W. and T. L. Grove (1993). "Experimental investigations of the role of H2O in calc-alkaline differentiation and subduction zone magmatism". *Contributions to Mineralogy and Petrology* 113(2), pages 143–166. DOI: 10.1007/bf00283225.

Spera, F. J. and W. A. Bohrson (2001). "Energy-Constrained Open-System Magmatic Processes I: General Model and Energy-Constrained Assimilation and Fractional Crystallization (EC-AFC) Formulation". *Journal of Petrology* 42(5), pages 999–1018. DOI: 10.1093/petrology/42.5.999.

Spiegelhalter, D. J., A. P. Dawid, S. L. Lauritzen, and R. G. Cowell (1993). "Bayesian analysis in expert systems". *Statistical Science* 8(3). DOI: 10.1214/ss/1177010888.

Streck, M. J. and W. P. Leeman (2018). "Petrology of "Mt. Shasta" high-magnesian andesite (HMA): A product of multi-stage crustal assembly". *American Mineralogist* 103(2), pages 216–240. DOI: 10.2138/am-2018-6151.

Streck, M. J., W. P. Leeman, and J. Chesley (2007). "High-magnesian andesite from Mount Shasta: A product of magma mixing and contamination, not a primitive mantle melt". *Geology* 35(4), page 351. DOI: 10.1130/g23286a.1.

Tepley, F. J., J. P. Davidson, and M. A. Clynne (1999). "Magmatic Interactions as Recorded in Plagioclase Phenocrysts of Chaos Crags, Lassen Volcanic Center, California". *Journal of Petrology* 40(5), pages 787–806. DOI: 10.1093/petroj/40.5.787.

Thy, P. and K. H. Esbensen (1993). "Seafloor spreading and the ophiolitic sequences of the Troodos Complex: A principal component analysis of lava and dike compositions". *Journal of Geophysical Research: Solid Earth* 98(B7), pages 11799–11805. DOI: 10.1029/93jb00695.

Till, C. B. (2017). "A review and update of mantle thermobarometry for primitive arc magmas". *American Mineralogist* 102 (5), pages 931–947. DOI: 10.2138/am-2017-5783.

Till, C. B., L. T. Elkins-Tanton, and K. M. Fischer (2010). "A mechanism for low-extent melts at the lithosphere-asthenosphere boundary". *Geochemistry, Geophysics, Geosystems* 11(10). DOI: 10.1029/2010gc003234.

Till, C. B., T. L. Grove, R. W. Carlson, J. M. Donnelly-Nolan, M. J. Fouch, L. S. Wagner, and W. K. Hart (2013). "Depths and temperatures of <10.5Ma mantle melting and the lithosphere-asthenosphere boundary below southern Oregon and northern California". *Geochemistry, Geophysics, Geosystems* 14(4), pages 864–879. DOI: 10.1002/ggge.20070.

Till, C. B., T. L. Grove, and M. J. Krawczynski (2012). "A melting model for variably depleted and enriched lherzolite in the plagioclase and spinel stability fields". *Journal of Geophysical Research: Solid Earth* 117(B6). DOI: 10.1029/2011jb009044.

Till, C. B., A. J. R. Kent, G. A. Abers, H. A. Janiszewski, J. B. Gaherty, and B. W. Pitcher (2019). "The causes of spatiotemporal variations in erupted fluxes and compositions along a volcanic arc". *Nature Communications* 10(1). DOI: 10.1038/s41467-019-09113-0.

Ueki, K. and H. Iwamori (2017). "Geochemical differentiation processes for arc magma of the Sengan volcanic cluster, Northeastern Japan, constrained from principal component analysis". *Lithos* 290–291, pages 60–75. DOI: 10.1016/j.lithos.2017.08.001.

Weidendorfer, D., M. W. Schmidt, and H. B. Mattsson (2017). "A common origin of carbonatite magmas". *Geology* 45(6), pages 507–510. DOI: 10.1130/g38801.1.

Wende, A. M., C. M. Johnson, and B. L. Beard (2015). "Tracing changes in mantle and crustal influences in individual cone-building stages at Mt. Shasta using U–Th and Sr isotopes". *Earth and Planetary Science Letters* 428, pages 11–21. DOI: 10.1016/j.epsl.2015.07.005.

Wieser, P. E., M. Edmonds, J. Maclennan, and J. Wheeler (2020). "Microstructural constraints on magmatic mushes under Kīlauea Volcano, Hawai'i". *Nature Communications* 11(1). DOI: 10.1038/s41467-019-13635-y.

Wieser, P. E., K. Iacovino, S. Matthews, G. Moore, and C. M. Allison (2022). "VESIcal: 2. A Critical Approach to Volatile Solubility Modeling Using an Open-Source Python3 Engine". *Earth and Space Science* 9(2). DOI: 10.1029/2021ea001932.

Wilkinson, M. D., M. Dumontier, I. J. Aalbersberg, G. Appleton, M. Axton, A. Baak, N. Blomberg, J.-W. Boiten, L. B. da Silva Santos, P. E. Bourne, J. Bouwman, A. J. Brookes, T. Clark, M. Crosas, I. Dillo, O. Dumon, S. Edmunds, C. T. Evelo, R. Finkers, A. Gonzalez-Beltran, A. J. Gray, P. Groth, C. Goble, J. S. Grethe, J. Heringa, P. A. 't Hoen, R. Hooft, T. Kuhn, R. Kok, J. Kok, S. J. Lusher, M. E. Martone, A. Mons, A. L. Packer, B. Persson, P. Rocca-Serra, M. Roos, R. van Schaik, S.-A. Sansone, E. Schultes, T. Sengstag, T. Slater, G. Strawn, M. A. Swertz, M. Thompson, J. van der Lei, E. van Mulligen, J. Velterop, A. Waagmeester, P. Wittenburg, K. Wolstencroft, J. Zhao, and B. Mons (2016). "The FAIR Guiding Principles for scientific data management and stewardship". *Scientific Data* 3(1). DOI: 10.1038/sdata.2016.18.

Wilson, C. R., M. Spiegelman, P. E. van Keken, and B. R. Hacker (2014). "Fluid flow in subduction zones: The role of solid rheology and compaction pressure". *Earth and Planetary Science Letters* 401, pages 261–274. DOI: 10.1016/j.epsl.2014.05.052.

Wolf, M. B. and P. J. Wyllie (1994). "Dehydration-melting of amphibolite at 10 kbar: the effects of temperature and time". *Contributions to Mineralogy and Petrology* 115(4), pages 369–383. DOI: 10.1007/bf00320972.

– (1995). "Liquid segregation parameters from amphibolite dehydration melting experiments". *Journal of Geophysical Research: Solid Earth* 100(B8), pages 15611–15621. DOI: 10.1029/95jb00660.

Yip, S. T. H., J. Biggs, M. Edmonds, P. Liggins, and O. Shorttle (2022). "Contrasting Volcanic Deformation in Arc and Ocean Island Settings Due To Exsolution of Magmatic Water". *Geochemistry, Geophysics, Geosystems* 23(7). DOI: 10.1029/2022gc010387.

Zydney, J. (2005). "Eighth-grade students defining complex problems: The effectiveness of scaffolding in a multimedia program". *Journal of Educational Multimedia and Hypermedia* 14(1), pages 61–90.