PERSPECTIVES

Trends in volcano seismology: 2010 to 2020 and beyond

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Abstract

Volcano seismology has been fundamental to our current understanding of crustal magma migration and eruption. The increasing availability of portable seismic networks with the creative use of seismic sources and ambient noise has led to a better understanding of the volcanic structure of many volcanoes and is producing increasingly detailed images of the volcanic subsurface. The past decade (2010-2020) has seen advances in our understanding of seismic sources under and surrounding volcanoes through precise locations, and through analysis of source mechanisms from seismic signals that are more varied and smaller in magnitude, reaching beyond traditional techniques. In tandem with continued research on fundamental physics-based understanding of volcano-seismic sources, new advances in computational analyses including machine learning methods will push our understanding of volcanic processes into the future. Incorporation of multidisciplinary geophysical observations (especially infrasound) has become commonplace, and our understanding of infrasound propagation and sources will feed back into our ability to monitor ongoing eruptions and surficial mass movements. Open-source codes will permit widespread evaluation and adoption of new methodologies for volcano-seismic analysis and inversion. Combined with quantitative and conceptual source models using improved structural constraints, these new methodologies will better characterize the range of volcano-seismic signal evolution scenarios and hold promise for creating better short-term forecasts. Finally, permanent instrumentation is available on an expanding range of volcanoes, and open data policies are increasingly making these data available to the scientific community in near real time.

This paper constitutes part of a topical collection: Looking Backwards and Forwards in Volcanology: A Collection of Perspectives on the Trajectory of a Science

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Introduction

Many volcanic processes, occurring both above and below the surface, generate seismic energy, and thus, the study of volcano seismology is a fundamental piece of volcano science. Seismology is a relatively mature field, having volcanic roots in the mid-nineteenth century and early twentieth century (Zobin 2017). This long history has led to a steadily improving understanding of the volcanic structure and processes that drive unrest and sometimes lead to eruptions (e.g., Minakami (1960), Omori (1911) Tokarev (1963); Eaton and Murata 1960).

A milestone multi-decadal comprehensive review by Chouet and Matoza (2013) provided a review of volcano seismology and attempted to forecast the future directions in the field. That publication, along with several others (e.g., Neuberg 2011; Nishimura and Iguchi 2011; Kawakatsu and Yamamoto 2015; McNutt and Roman 2015; Zobin 2017; Saccorotti and Lokmer 2021), provides a review of the "state of the art," including an in-depth discussion of volcanic

event types and source models, tying in fluid mechanics along the way.

With respect to future directions, Chouet and Matoza (2013) summed up the future of volcano seismology as follows:

> The key to a better understanding of volcanic processes lies in a sustained effort aimed at cross-fertilization between increasingly realistic numerical and experimental models of the fluid dynamics and elastodynamics, spatially and temporally dense field measurements of diverse geophysical signals at all frequencies, and chemical and physical evidence recorded in the eruptive products.

This forecast of sorts has been largely true, especially as it pertains to numerical models, where the so-called physics-based models have become more commonplace (Anderson et al. 2019). There have also been considerable advances in obtaining increasingly detailed measurements of seismic signatures of unrest and eruption (observational seismology) with a plethora of different instrumentation and methodologies, as we will explore below.

In this paper, we aim to summarize succinctly the past 10 years of progress and attempt to project future trends. The topic is worthy of an entire volume, so we have chosen to focus on methods and trends within volcano seismology that improve our ability to forecast volcanic eruptions. For more in-depth discussions of volcano seismology as a field, we refer the reader to the summary publications above.

Illuminating the magmatic plumbing system

Understanding the subsurface structure of a volcano, including the magmatic and hydrothermal plumbing system, is crucial to building a conceptual model of the volcano and offers a framework from which to interpret seismicity occurring in different parts of the volcano.

Seismology currently broadly offers three main ways to obtain constraints on the spatiotemporal structure volcanic subsurface fluid pathways: (1) tomographic imaging of elastic parameters, (2) mapping seismicity distributions and characteristics, and (3) waveform inversions for moment-tensor and single-force representation of sources, which can constrain geometries of key elements in the fluid pathway structure. The three topics above are complementary, and each offers insights at different scales and resolutions.

Seismic tomography (broadly defined) continues to be a fundamental tool for understanding volcanic structure (e.g., Iyer and Dawson (1993); Lees 2007; Koulakov and Shapiro 2021). Ambient noise tomography studies, often in conjunction with other methods, have imaged the S-wave structure under volcanoes (Lin et al. 2014; Kiser et al. 2016;

Ulberg et al. 2020), where S-wave travel times are sparse in the seismic catalog (Nagaoka et al. 2012; Jaxybulatov et al. 2014; Flinders and Shen 2017; Heath et al. 2018; Green et al. 2020; Miller et al. 2020). Towards the end of the 2010-2019 decade Janiszewski et al. (2020) and Portner et al. (2020) have illuminated the mid and lower crust of volcanoes using receiver functions within sparse networks. Advances in time-dependent (4D) tomography (Koulakov et al. 2013; Vargas et al. 2017; Koulakov and Vargas 2018) have revealed temporal changes in the ratio between the p-wave velocity and s-wave velocity, which have been interpreted as relating to magma storage and transport structures. Full-waveform inversion tomography (FWI; Beachly et al. 2012; Heath et al. 2018) has also improved the spatial resolution where applicable. Currently, the best resolution lies between about 2 and 10 km depth, with the shallower depths limited by station spacing and frequency content and the deeper areas limited by the difficulty of maintaining a dense station coverage within a large aperture network and by lack of deep local earthquakes. We note that the majority of shallow pre- and co-eruptive seismicity occurs at depths < 5 km; thus, imaging the shallow structure remains an important target of future work.

Imaging of the magmatic plumbing system is improving through denser instrumentation and active seismology strategies and techniques, borrowed in part from industry exploration seismology (e.g., Sheriff and Geldart 1995; Keho and Kelamis 2012; Nishimura et al. 2021). Full-waveform inversion (FWI) applied to experiments carried out over mid-ocean ridges (e.g., Arnulf et al. 2012, 2014; Carbotte et al. 2021) has delineated mush zones, melt rich zones, and conduits. Transferring this resolution to rugged and remote subaerial volcanoes will be difficult not only because of the difference in impedance contrasts but also because remote seismometer placement is strenuous and artificial seismic sources are difficult to permit in wilderness, sacred areas, or fragile ecosystems. The proliferation of highly portable, low-cost seismometer/digitizer combinations, commonly called nodes, may mitigate some of this difficulty. Whereas experiments with fully buried sensors and power systems at the surface were considered state-of-the-art in the late 2000s (e.g., Aoki et al. 2009; Zandomeneghi et al. 2010, 2013; Beachly et al. 2012), experiments with many hundreds or thousands of instruments, including nodes, were occurring throughout the 2010s (Mount St. Helens (iMUSH): Kiser et al., 2016; Ulberg et al. 2020; Yellowstone: Garcia 2017; Wu et al. 2017; Ward and Lin 2017) (Fig. 1). One new type of instrument currently in its infancy and developed in the oil and gas industry is distributed acoustic sensing (DAS), which uses fiber-optic cables to sense strain rates at meter-scale spatial sampling along the length of the fiber (Lindsey et al. 2017). Temporary fiber-optic cables have been installed on some volcanoes such as Iceland (Jousset et al.,
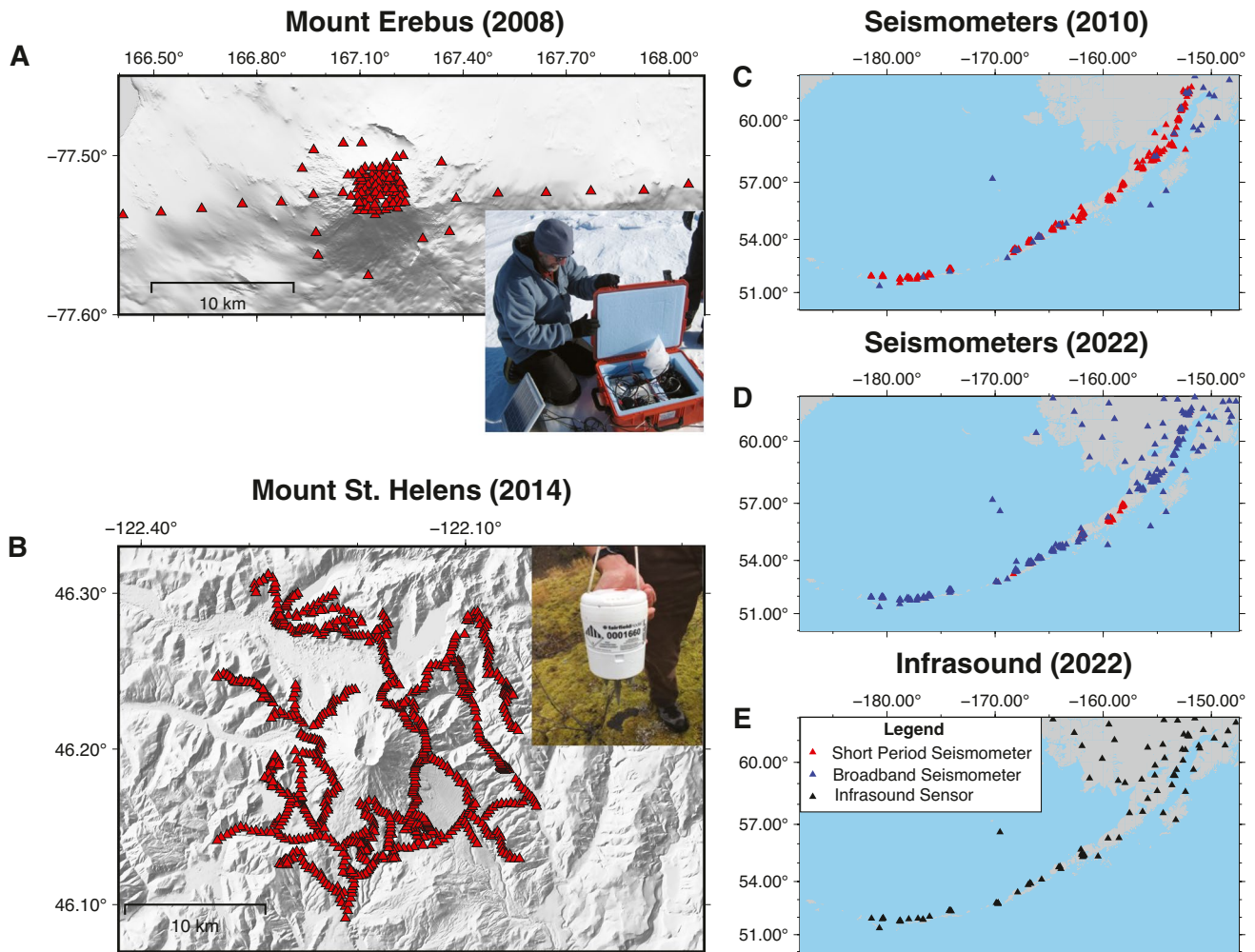
Fig. 1 Comparison of deployments and instrument improvements through the last decade. **A** An 80-station network on Erebus volcano, Antarctica, carried out in 2008 (Zandomeneghi et al. 2010). Red triangles are the broadband stations. In the inset is the typical setup for this experiment, where the power and digitization occur above ground (inside the orange box) and the instrument is buried underground (Photo Credit: Tomo Erebus and IRIS PASSCAL field team). **B** A subset of stations (red triangles) deployed for the iMush experiment at Mount St. Helens in 2014 (Hansen and Schmandt 2015). In this experiment, approximately 900 nodes were deployed. The inset on the bottom is a picture of a node, illustrating the small size and compact nature of the seismic instrument (Photo Credit: Amanda Thomas). Both maps in A and B are plotted at the same scale. **C** Improvements in seismic and infrasound instrumentation on Alaskan volcanoes. Maps consider instrumentation up to 2010 (C.), 2022 (D.), and infrasound instrumentation in 2022 (E.). Red triangles refer to analog short period seismic instruments, triangles refer to digital broadband seismic instruments, and black triangles refer to infrasound sensors. GNSS sites are not shown. All maps in C, D, and E are plotted at the same scale. Maps were created with pyGMT (Uieda et al. 2021) and GMT (Wessel et al. 2019). Erebus digital elevation model from the REMA dataset (Howat et al. 2019)

2018), Mount Etna (Currenti et al. 2021), Azuma volcano (Nishimura et al. 2021), and Mount Meager (Klaasen et al. (2021)), but the real potential in the short term is in using existing fiber-optic cables (dark fiber) that run along roads around some volcanoes (e.g., Ajo-Franklin et al. 2019).

Natural earthquake sources and artificial blasts generate seismic waves with wavelengths that are significantly larger than most structures within a magma transport system, resulting in a smeared or blurry tomographic image. Recently, active seismic sources common in exploration geophysics, such as vibroseis trucks, have been deployed in volcanic settings. Waves from these seismic sources, when recorded on a large number of instruments, can image the crust in much greater detail than traditional active source or passive experiments because the seismic energy that is transmitted is broadband and well characterized. This strategy has been recently applied at Solfatara volcano (Bruno et al. 2017), Yellowstone (Brandon Schmandt, pers. Comm.), and is proposed at the summit of Kilauea in 2023 (Roger Denlinger, pers. Comm.). Creative uses of active sources, natural earthquake sources, and ambient noise in combination with large numbers of nodes

or fiber optic cables will continue to sharpen our image of the subvolcanic structure for decades to come.

Tracking magma dynamics

As magma, magmatic gases, and subsurface fluids move through the crust, they may change local stresses or build up pressure that is released in the form of earthquakes and/or tremor. In the past decade, one well-demonstrated new technique is the use of network-wide matched filtering, using larger earthquakes to detect smaller earthquakes. Matched filtering combined with high-precision earthquake location studies of swarms at several volcanoes (e.g., Shelly and Hill 2011; Matoza et al. 2014; Shelly et al. 2015; Hotovec-Ellis et al. 2018; Wech et al. 2020) has shown that the small earthquakes connect the dots between the larger earthquakes, showing us details of magma and fluid migration that aren't obvious using the standard seismic catalog alone.

Especially during times of unrest or eruption, much of the seismic energy release may be in the form of tremor, long-period or very-long period earthquakes; those types of events often attributed to fluid and gas movement through the crust. Yet, there remains ambiguity in the source processes responsible for such events, which is especially problematic in the midst of an unrest sequence when assessing the volcanic hazard is critical. The past decade has seen advances in our ability to detect and locate some of these nontraditional sources (e.g., Dawson et al. 2010; O'Brien et al. 2011; Haney 2014; Soubestre et al. 2018), and when interpreted within the context of a well-determined conceptual model, these advances have improved our understanding of magma dynamics.

Understanding the source mechanisms of earthquakes within a period of unrest can give critical insights into important components of the magmatic plumbing system (such as a geometrical conduit discontinuity). Source mechanism solutions have become increasingly available, especially for larger earthquakes and/or very long periods (e.g., Chouet and Dawson 2011; Ágústsdóttir et al. 2019; Roman et al. 2021; Alvizuri et al. 2021). Polarity-derived source mechanisms can be resolved at smaller magnitudes by using the sign of the cross-correlation coefficient of similar events or by stacking (Shelly et al. 2016; Wech et al. 2020), and in areas with improved constraints on structure and velocity (see above), full-waveform inversion has become possible on increasingly smaller events by detecting and stacking similar events (Matoza et al. 2015; Lyons et al. 2016). On the other hand, extending waveform inversion to higher frequencies in the LP band (0.5 to 5 Hz) will rely on the ability to create Green's functions that accurately take into account topography and small-scale velocity heterogeneities, especially in the shallowest hundreds of meters (Gabrielli et al.

2020). Characterizing the near-surface velocity structure should become more feasible with the future use of nodes in dense deployments above volcano-seismic sources. Future development in this area will continue to focus on obtaining broadband seismic source mechanisms for a larger number and variety of events and for higher source frequencies with improved velocity models. Moving beyond a point-source representation of the seismic source, extended (finite source) inversions (Ji et al. 2002) may become increasingly feasible in volcano seismology (Nakano et al. 2007; Chouet et al. 2008).

Insights into near-surface processes

Shallow volcanic processes such as fissuring, explosions, and surface flows can pose immediate hazards to nearby populations and infrastructure while also creating infrasonic waves in the atmosphere (Matoza et al. 2019; Watson et al. (n.d.)). Combining seismic and infrasound observations has been fruitful for understanding near-surface processes (Matoza et al. 2009; Lyons et al. 2016; Allstadt et al. 2018; McKee et al. 2018; Neal et al. 2019; Fee et al. 2021), and atmospheric propagation conditions commonly permit remote detection (> 250 km) of large explosive eruptions (Matoza et al. 2011, 2017; De Angelis et al. 2012). There has been significant exploration of the effects of the atmosphere and topography on recorded infrasound waveforms in the last 10 years, which has demonstrated the need to consider topography especially at local (< 15 km) to regional (15–250 km) distances (Kim et al. 2015) and illustrated the utility and present limitations of operational atmospheric models for understanding infrasound recording in the far field (Schwaiger et al. 2019). Taken together, these advances have allowed study into more sophisticated explosive eruption source models (Matoza et al. 2013; Haney et al. 2018). A better understanding of the explosion source type and impacts on recorded waveforms holds the promise in the future of making infrasound a useful tool for estimating the mass discharge rate of an explosion, a critical component in ash modeling and hazard assessment (e.g. Lamb et al. 2015; Fee et al. 2017; Perttu et al. 2020).

Many types of surface flows (avalanches, rockfall, debris flows) are recorded both seismically and infrasonically and represent a type of volcanic hazard that is independent of unrest. Recent observations of debris flows with infrasound (e.g., Kogelnig et al. 2014; Johnson and Palma 2015; Marchetti et al. 2019) illustrate the utility of infrasound to record debris flows and, along with seismic instrumentation, can form the basis for lahar and debris flow warning systems. While debris flow detection is feasible in an operational setting, calculating volumes and other flow characteristics

represents significant challenges moving forward (Allstadt et al. 2018).

Advances in computing

The rise in availability of cloud and cluster computing resources, as well as continued improvements in personal computing, has enabled the scale of modeling complexity and processing of large volcanic datasets to expand; however, large volumes of data generated by new technologies, such as nodes and DAS, currently present problems for data archiving, processing, and sharing. Emerging techniques in data processing can now produce additional time series (e.g., seismic velocity change from ambient noise interferometry (Brenguier et al. 2008)) to supplement traditional seismic monitoring. Further, Green's functions and synthetic seismograms are being extended to higher frequencies, improving FWI tomography and full moment tensor inversions of seismic and infrasound data. Following broader trends in the software community, many codes for techniques discussed in this paper are open source and freely available. This represents a huge step forward in volcano seismology for two reasons: (1) techniques can be more easily applied and evaluated on additional eruption data, and (2) open-source codes have a better chance of being operationalized in an observatory environment, potentially improving real-time eruption forecasts. The inclusion of code specifically designed to reproduce published results (e.g. Jupyter Notebooks) is also an exciting recent trend.

During unrest, high earthquake rates can easily overwhelm analysts and offer an opportunity for automated techniques, including machine learning, to locate and classify earthquake signals. In the 2010s, there was a revolution in machine learning that has enabled the development of new methods and applications with the use of industry standard open-source libraries (e.g., Scikit-learn, Pedregosa et al. 2011; TensorFlow, Abadi et al. 2015; PyTorch, Paszke et al. 2019). While machine learning approaches have been used previously in volcano seismology for event classification (e.g,. Falsaperla et al. 1996; Benítez et al. 2007; Hibert et al. 2017) and detection (Dawson et al. 2010), differences in station density, local path effects, and event definitions between volcanic centers have previously limited the widespread application of machine learning despite the increasing availability of computational resources (see Carniel and Raquel Guzmán 2021, for an in-depth review). Recent analyses of synthetic datasets have been used with success to create new generic detectors and locators that hold the promise to perform well in high-event rate environments where standard pickers break down (e.g,. Zhu and Beroza (2019); Ross et al. 2019; Walter et al. 2021). Another approach simplifies the creation of a training dataset by using the existing seismic catalog in Hawaii for a convolutional neural network to detect and locate earthquakes (Shen and Shen 2021). Both approaches have open-source codes available, making their application to other systems simpler (Walter et al. 2021; Shen and Shen 2021). Automated earthquake classification using machine learning has seen advances in multi-station approaches (Maggi et al. 2017) and multi-volcano approaches (Bueno et al. 2020; Cortés et al. 2021).

The next decade (2020-2029) of volcano seismology will inescapably include machine learning, applied to a variety of problems using open-source codes on more readily available high-performance computing (HPC) resources. Still, at present, machine learning remains a sophisticated type of pattern matching and thus is not sufficient by itself without also incorporating an understanding of fundamental underlying physical processes that give rise to seismicity.

New datasets

Over the past decade, advances in low-power electronics, compact broadband instruments and recording systems, and direct burial instruments have accelerated the installation of a wide range of instrumentation at a broader suite of volcanoes, such as broadband seismometers, infrasound, and real-time GNSS (Fig. 1). Within the USA and a few other localities, real-time data are available publicly within a few seconds of being acquired. The utility of high-quality, real-time data availability was most recently illustrated during the 2018 Kīlauea eruption, where publications have been varied and numerous. The proliferation of diverse and high-quality instrumentation has the potential to provide more high-quality datasets for more unrest and eruption sequences on a range of different volcanoes. While this represents an opportunity for scientists to apply their favorite algorithms, it is important to coordinate with the individuals or groups with which the data originated. Communication will be important to enable collaboration and prevent duplicate efforts between groups with common interests and efforts. The next 10 years will inevitably see more instrumentation density on a broader range of volcanoes and installation of new equipment. This instrumentation will ideally act as a backbone for large collaborative community experiments at volcanoes of interest. Challenges also remain in the timeliness of instrument deployments during periods of unrest, especially at undermonitored volcanoes.

Summary

Improving volcanic forecasts is a goal that underpins much of volcano seismology. Advances in our understanding of the structure of the magmatic plumbing system and

improved constraints on the processes within that system can feed into the development of a conceptual model that is useful for forecasting, which will have the most impact on the short-term forecasts of activity on well-instrumented volcanoes. Machine learning techniques will help in improving short-term forecasts; however, to extend the forecast window beyond our current capabilities, the magmatic system constraints from volcano seismology need to be incorporated with constraints from other disciplines into physics-based models (Chouet and Matoza 2013; Manga et al. 2017) (Fig. 2). Contributions from laboratory experiments and field observations will also elucidate plausible source mechanisms (e.g.,, Kendrick et al. 2014; Arciniega-Ceballos et al. 2015; Capponi et al. 2017; Spina et al. 2018). While there are common characteristics at many volcanoes, each is unique with its own unrest and eruptive characteristics. Physics-based models will be needed to capture these differences and attempt to understand what is going on during the inter-eruptive time periods between the end of the last eruption and the start of precursory unrest.

The next 10 years of volcano seismology promise to take advantage of several broader trends in hardware technology, open-source software development, and high-performance computing resources to push our understanding of volcanoes forward. There currently exists a gap between those techniques published in the literature and those operationalized in an observatory environment. HPC and open-source software concepts will help to close the gap between the research and operational worlds, eventually improving our ability to provide accurate and timely forecasts of volcanic activity.
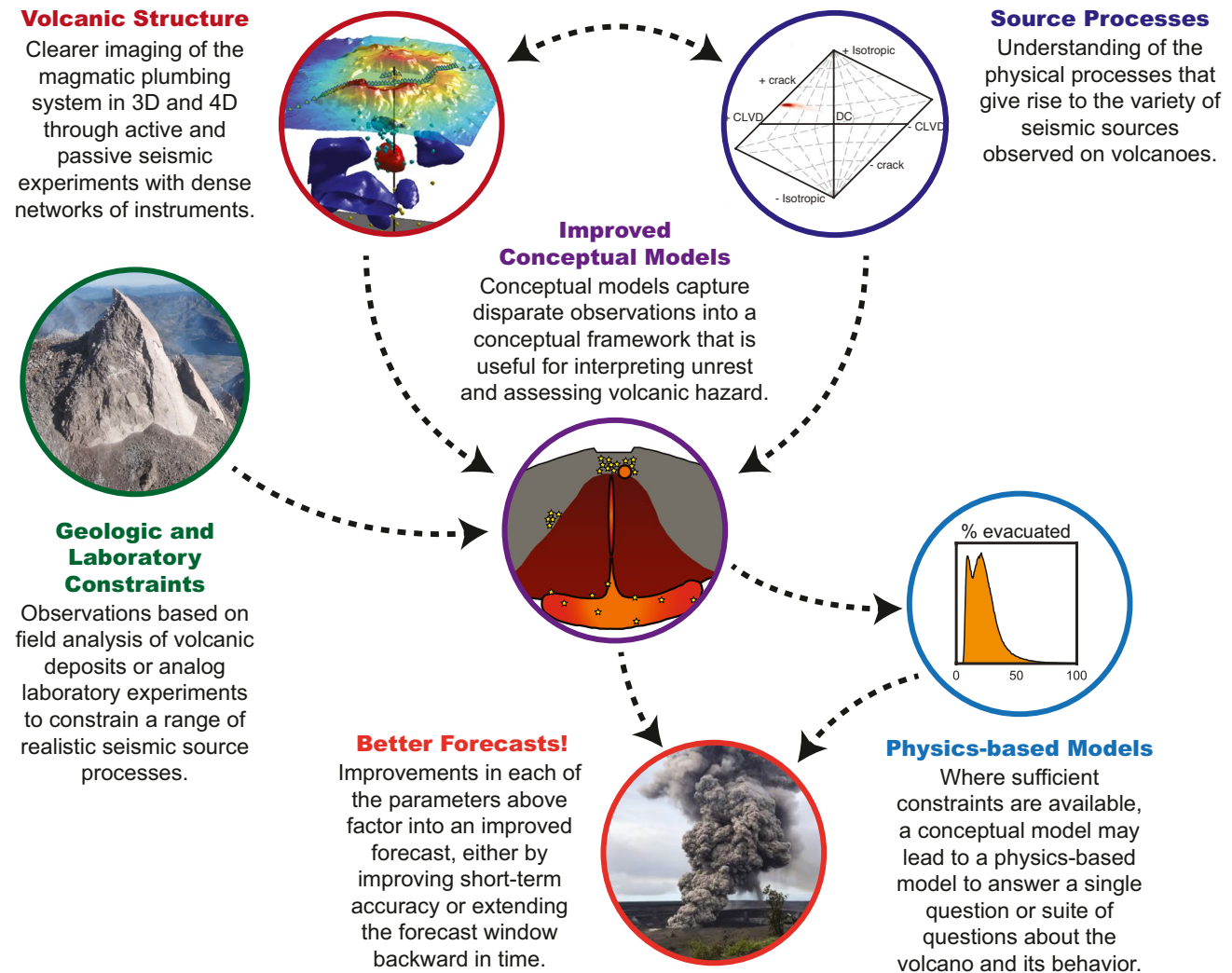

Fig. 2 Flowchart showing how the different constraints of volcano seismicity integrate into a better forecast of volcanic activity. Volcanic structure image from Heath et al. (2015). Source process figure from Wech et al. (2020). Physics-based models image modified from Anderson et al. (2019). Photographs are courtesy of the USGS

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