Bulletin of Volcanology (2022) 84: 72
https://doi.org/10.1007/s00445-022-01582-4

PERSPECTIVES

Volcanotectonics: the tectonics and physics of volcanoes and their eruption mechanics

Agust Gudmundsson[1] · Kyriaki Drymoni[2] · John Browning[3] · Valerio Acocella[4] · Falk Amelung[5] · Fabio L. Bonali[2] · Abdelsalam Elshaafi[6] · Ines Galindo[7] · Nobuo Geshi[8] · Adelina Geyer[9] · Michael J. Heap[10,11] · Özgür Karaoğlu[12] · Shigekazu Kusumoto[13] · Joan Marti[9] · Virginie Pinel[14] · Alessandro Tibaldi[2] · Thorvaldur Thordarson[15] · Thomas R. Walter[16]

Received: 18 February 2022 / Accepted: 23 June 2022 / Published online: 8 July 2022

Abstract
The physical processes that operate within, and beneath, a volcano control the frequency, duration, location and size of volcanic eruptions. Volcanotectonics focuses on such processes, combining techniques, data, and ideas from structural geology, tectonics, volcano deformation, physical volcanology, seismology, petrology, rock and fracture mechanics and classical physics. A central aim of volcanotectonics is to provide sufficient understanding of the internal processes in volcanoes so that, when combined with monitoring data, reliable forecasting of eruptions, vertical (caldera) and lateral (landslide) collapses and related events becomes possible. To gain such an understanding requires knowledge of the material properties of the magma and the crustal rocks, as well as the associated stress fields, and their evolution. The local stress field depends on the properties of the layers that constitute the volcano and, in particular, the geometric development of its shallow magma chamber. During this decade an increasing use of data from InSAR, pixel offset and structure-from-motion, as well as dense, portable seismic networks will provide further details on the mechanisms of volcanic unrest, magma-chamber rupture, the propagation of magma-filled fractures (dikes, inclined sheets and sills) and lateral and vertical collapse. Additionally, more use will be made of accurate quantitative data from fossil and active volcanoes, combined with realistic numerical, analytical and machine-learning studies, so as to provide reliable models on volcano behaviour and eruption forecasting.

Keywords Volcano monitoring · Magma-chamber · Magma plumbing system · Dike propagation · Caldera collapse · Eruption forecast

Introduction

Volcanotectonics is a discipline that has emerged over the past four decades, but its roots are much older. In this brief overview, the focus is on the tectonic/structural geology studies that shaped our initial understanding of volcanotectonics, the development of mechanical models provided to explain magma emplacement, the testing of these models during important eruptive events and finally a summary of how we see the discipline developing in the future. Because of the space limitations, many volcanotectonic topics are here treated very briefly (and some hardly at all), the focus being on those that we regard as the most important and relevant for this brief. While we aim at giving a general view of the main topics presented, for some points there may be other valid perspectives — for example, as to the scope of volcanotectonics — that are not reflected in the present short overview.

While the details of how volcanoes function is still a topic of active research, how they form is now well understood. Yet, as late as the early nineteenth century the formation of volcanoes was not generally understood. 'Craters of elevation', a prominent idea at the time, suggested that volcanoes/volcanic islands such as Etna, Santorini and some of the Canary Islands formed through a sudden upheaval of an originally

---

Editorial responsibility: J.H. Fink

This paper constitutes part of a topical collection:

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

✉ Kyriaki Drymoni
kyriaki.drymoni@unimib.it

Extended author information available on the last page of the article

horizontal pile of lava flows erupted on the sea floor (Elie de Beaumont and Leopold von Buch — the latter introduced the Spanish term ‘caldera’ into volcanology). Later studies by Charles Lyell and others, however, demonstrated that polygenetic volcanoes form over long periods of time through the accumulation of eruptive and intrusive materials (cf. Geikie 1905; Adams 1938; Wilson 1998).

Volcanotectonics is a subfield of volcanology that uses techniques from tectonics/structural geology combined with appropriate principles from physics, including rock physics, fracture mechanics and fluid mechanics. The focus of volcanotectonics is on understanding physical processes that occur within and beneath volcanoes and the combination of research on fossil and deeply eroded volcanoes with those of active volcanoes.

Tectonic/structural geology studies of volcanoes

The roots of volcanotectonics lie in studies of volcanic structures in the second half of the nineteenth century. An early focus was on dikes (Fig. 1a, c), for the obvious reason that they were known to be the principal feeders to eruptions (Geikie 1905). Much of the structural/tectonic data on dikes collected during the nineteenth century through field studies in the UK, with references to other areas such as the USA, Iceland, Italy and India, is presented by Geikie (1897). Whilst Geikie did not use the term ‘extension fracture’, the relationships between cross-cutting dikes demonstrate that dikes most commonly occupy extension fractures and rarely use faults as paths. Further description of Geikie’s interpretations is presented in the supporting information, as well as a summary of several dike-related structural topics absent from his overview. Briefly, these topics include inclined sheets, dike-fracture formation and the relation between dike strike and stress fields and other mechanical aspects.

Mechanical models of magma chambers and sheet intrusions

Magma chambers are a necessary condition for the formation and activity (such as dike/sheet injections and eruptions, caldera collapses and geothermal fields) of polygenetic volcanoes (Gudmundsson 2020). Formation,

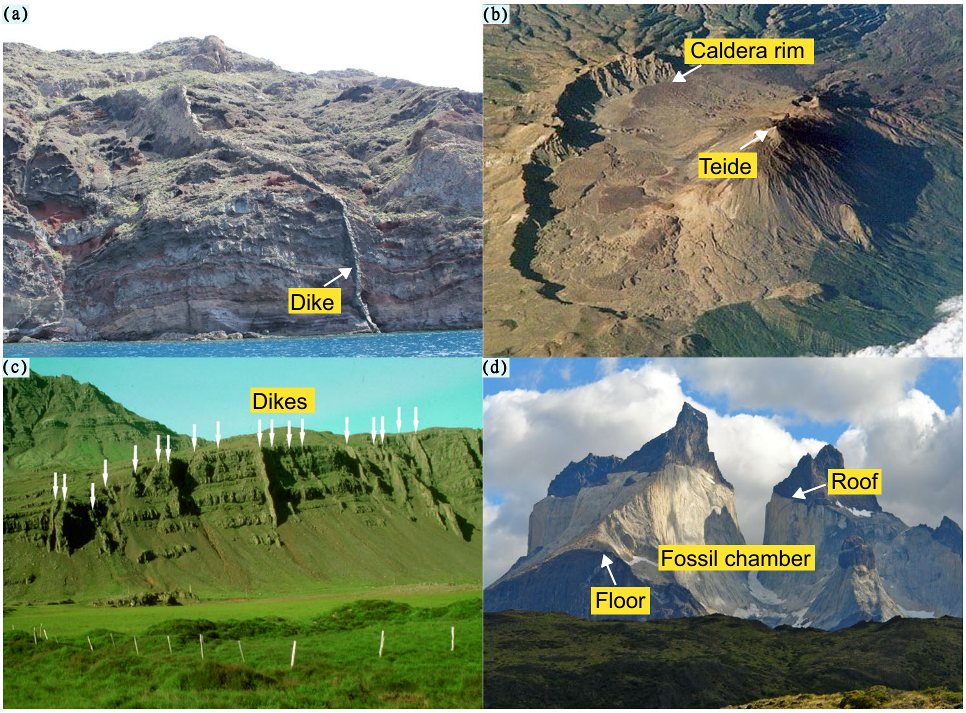

Fig. 1 Examples of volcanotectonic structures. **a** A local radial dike (thickness: 1.5 m) dissecting the northern caldera wall of the Santorini volcano, Greece. **b** The Las Cañadas caldera (rim indicated) and the stratovolcano Teide, the Canary Islands. The major axis of the caldera is about 17 km, the minor axis about 9 km, and maximum height of the caldera wall is about 500 m (photo: NASA). **c** Part of a regional dike swarm (mean thickness 5.5 m) dissecting a basaltic lava pile in East Iceland. Most of the dikes, here about 1.2 km below the surface at the time of their emplacement, are indicated by white arrows. **d** The Torres del Paine laccolith/sill in Chile, a fossil shallow magma chamber, mostly of granite but underlain by a mafic pluton (photo: Evelyn Proimos/Flickr). The felsic part seen here is about 2-km thick, with a well-exposed floor and roof, and was emplaced at 2–3 km depth below the active volcanic area at the time (Michel et al. 2008)

mechanical development and rupture (during unrest) of magma chambers are active research topics within volcanotectonics but with original ideas conceived in the nineteenth century. Perhaps the first attempt to explain volcanic structures observed in the field in terms of a mechanical model was made by Gilbert (1877) in his study of the formation of the laccoliths of the Henry Mountains of Utah in the USA. Since many shallow magma chambers are laccoliths which, in turn develop from sills, these may be regarded as the first mechanical models on the formation of magma chambers.

Most volcanic eruptions are supplied with magma through dikes. Understanding the mechanics of dike emplacement is thus of fundamental importance for successful eruption forecasting. There can be no progress in understanding dike/sheet propagation and eruption unless it is clear what mechanical type of fracture they are. The first mechanical model of dikes was provided by Anderson (1905, 1951). He understood that most dikes are fluid-driven fractures, that is, extension fractures, formed in a direction perpendicular to the minimum principal compressive stress. (This conclusion was also reached by Hubbert and Willis (1957) who pointed out that dikes are analogous to human-made hydraulic fractures.) Anderson suggested, using results from Inglis (1913), that, theoretically, high tensile stress will concentrate at the tip of an overpressured dike — his proposed 'wedging action' (Anderson 1951) — encouraging its propagation.

Anderson further recognised that sills (hence, many shallow magma chambers) and inclined sheets are also extension fractures and modelled the latter as such (Anderson 1936). These conclusions were generally accepted, although some suggested inclined sheets were shear fractures (e.g. Robson and Barr 1964; Phillips 1974). These suggestions could plausibly be entertained at that time when extensive tectonic data on inclined sheets were not available. Studies of thousands of inclined sheets in many active and extinct volcanoes over the past decades show, however, that the great majority of inclined sheets are extension fractures (Gudmundsson 2020).

As regards local stresses in volcanoes, Anderson (1936) was the first to apply a nucleus-of-strain model (the general solutions were initially derived by Melan, 1932, and also by Mindlin, 1936) to explain the orientation of the stress trajectories that largely determine the paths of inclined sheets and dikes. Anderson (1936) also used the model to provide the first mechanical explanation for the formation of ring-dikes and, therefore, of ring-faults associated with collapse calderas (Figs. 1b and 2).

Subsequently, Mogi (1958) used the nucleus-of-strain model to explain the surface deformation of volcanoes resulting from pressure changes in a magma chamber. In volcanology, this is known as a point-pressure or Mogi model and has been widely used for decades. The model is of great use for estimating the depth to the pressure source, the magma chamber (Chaussard and Amelung 2014). Because it assumes an elastic half space (no layering) and a chamber without a well-constrained size or shape, the Mogi model is less useful to infer the stress conditions for magma-chamber rupture (and dike/sheet injection) or ring-fault formation. For the latter, numerical models for chambers of various sizes and shapes (Figs. 1d and 2), hosted by layered crustal segments (Fig. 1a, c), are considered more useful (Gudmundsson 2020).

Similarly, elastic-dislocation models, initially used for faults (Steketee 1958a, b; Press 1965), have been widely applied to dikes (Okada 1985, 1992; Dzurisin 2006; Segall 2010). The primary use of such models is for the inversion of surface-deformation data to infer dike (and inclined sheet and sill) opening/thickness, attitude and depth assuming, again, that the crustal segment behaves as an elastic half-space. Numerical models on dikes began in the late 1970s (Pollard and Holzhausen 1979; cf. Pollard and Fletcher 2005; Rivalta et al. 2015). While the early models assumed elastic half-spaces, increasingly realistic layered models are now fast becoming the rule (e.g. Manconi et al. 2007; Masterlark 2007; Kinvig et al. 2009; Marti et al. 2016; Bazargan and Gudmundsson 2019; Drymoni et al. 2020; Clunes et al. 2021).

All the early models were significant steps forward in tectonic studies of volcanoes. They are still widely used, but the general trend now is towards more realistic models (including layered crustal segments, magma sources of various shapes and existing faults) using numerical techniques. These make it possible to make models that, in combination with results from theories of composite materials, fracture and analytical mechanics, and the in situ and upscaled physical properties of volcanic rocks (Heap et al. 2020; Heap and Violay 2021), permit forecasts of magma-chamber rupture (Fig. 1d) during unrest periods (Browning et al. 2015) and determination of the likely propagation paths of the resulting intrusions (Figs. 1a and 2; Gudmundsson 2020; Davis et al. 2021).

Recent events that have shaped volcanotectonics

The first textbooks that explicitly define the discipline of volcanotectonics were published only in the past decade (Gudmundsson 2011, 2020; Acocella 2021). This is a testament to the discipline's novelty. The development of the discipline has also been influenced by observations from several comparatively recent volcanic eruptions, caldera collapses and unrest periods. All these observations have provided constraints on the underlying physics that control magma emplacement and eruptions and have led to an enhanced understanding that now forms the basis of reliable eruption

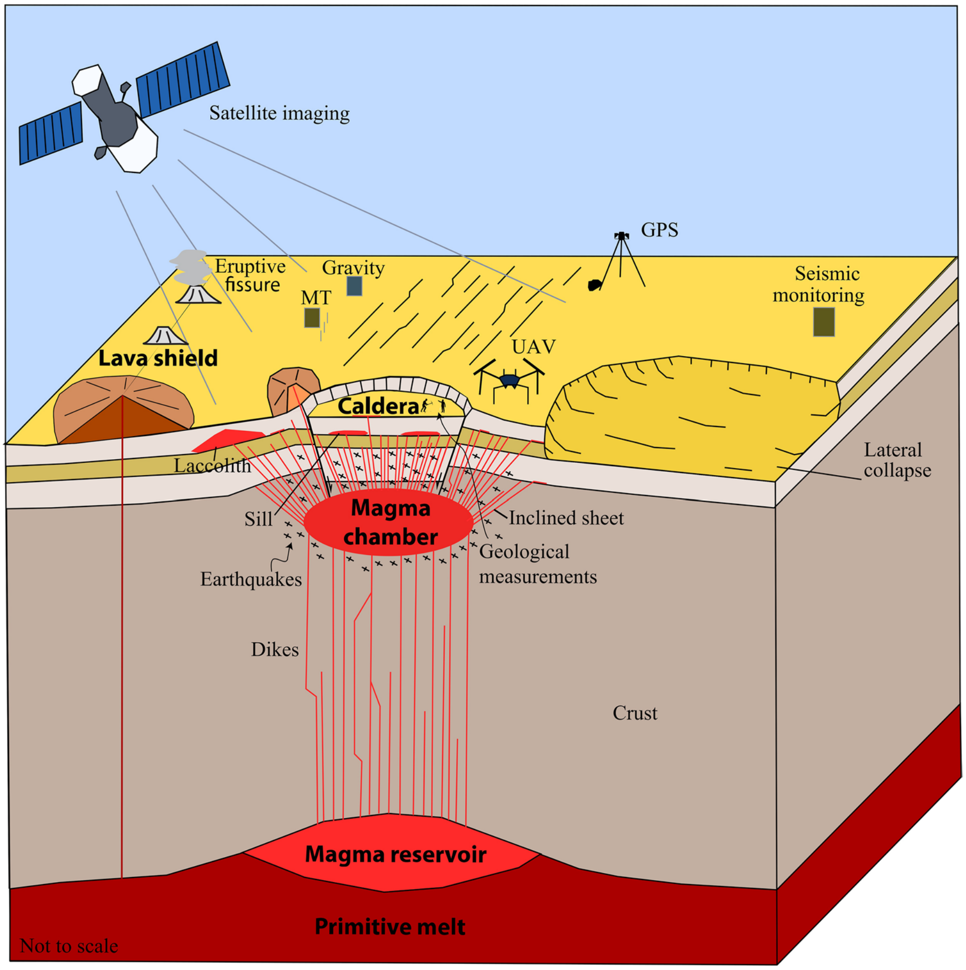

Fig. 2 Schematic illustration of a typical internal structure (plumbing system) of a polygenetic volcano with a collapse caldera, inclined sheets, sills, dikes and mechanical layering. The primitive lava shield is fed directly from the deep-seated reservoir which also supplies magma (through dikes) to the shallow magma chamber. The shallow chamber expands and generates earthquakes (indicated by crosses) and, over time, injects numerous radial dikes and inclined sheets most of which become arrested at contacts between mechanically dissimilar rocks while some feed sills, a laccolith and eruptions. The former volcanic edifice has been subject to vertical (caldera) and lateral (landslide) collapses. Also shown are the main techniques for real-time monitoring of volcanotectonic processes. These include geological measurements and studies, satellite imaging (including interferometric synthetic aperture radar (InSAR)), magnetotelluric (MT) studies, gravimetric studies, unmanned aerial vehicle (UAV) or drones and global positioning system (GPS)

forecasting, an ultimate goal in volcanology (Sparks 2003; Roman and Cashman 2018).

The formation of calderas and landslide scarps can provide access to the inner workings of the volcano. For example, the 2000 summit collapse of the Miyakejima volcano in Japan exposed series of arrested dikes and feeder-dikes within the caldera walls (Geshi et al. 2002, 2020). In fact, many caldera walls are ideal for studying the inner workings of volcanoes since the scarps record important information about past magma paths and fault slips (Drymoni et al. 2021). More recently, the well-monitored caldera collapse at the summit of Kīlauea (USA) in 2018 (Anderson et al. 2019; Tepp 2021) permitted unprecedented temporal coverage of a collapse and allowed frictional properties of the collapse faults to be constrained (Segall and Anderson 2021). A significant contribution to our understanding of caldera collapse derives from analogue models which, when combined with field observations and numerical models, are powerful tools in gaining insight to the underlying processes (Roche et al. 2000; Bosworth et al. 2003; Lavallée et al. 2004; Acocella 2007; Geyer and Marti 2008, 2014).

In the 1970s and 1980s, it was recognised from measurement of unrest events in Iceland and Hawaii (USA) that dike propagation induces earthquake swarms, and numerous such observations have been made since (Passarelli et al. 2015). Recently, there have been real-time observations of dike propagation, as inferred from induced seismicity (Agustsdottir et al. 2016). Despite high-quality instrumental monitoring of dike propagation during unrest periods in many volcanoes (Fig. 2), successful forecasting of dike-fed eruptions is still rare. A well-known example of forecasting is the Plosky-Tolbachik (Russia) 1975–76 eruption which was preceded by strong seismic precursors and could be predicted one week in advance (Fedotov et al. 1980). Similarly, the 2000 eruption of Hekla, Iceland, was forecasted within hours due, primarily, to the signal from one fortuitously located borehole strainmeter that recorded the opening of a dike, with separate complementary measurements of the preceding seismicity (Sturkell et al. 2013).

Both these, and other similar, forecasts are purely empirical, and their success depends on the assumption that the behaviour of the volcano is essentially the same prior to each eruption. Over time periods that are short in comparison with the lifetime of a volcano, the behaviour during unrest that eventually results in an eruption may, indeed, be basically the same. But given that volcanoes are highly dynamic systems whose mechanical properties, local stresses, and magma-source geometries and sizes are continuously changing, the assumption that purely empirical methods can be used to make reliable forecasts of volcanic eruptions is not evidence-based. For example, the 2012–13 Plosky-Tolbachik (Russia) eruption was not preceded by any strong seismic precursor and could not be forecasted (Caudron et al. 2015). Reliable forecasts, in general, must rest on an understanding of the physical principles that control magma-source rupture and magma movement from the source to the surface. Those principles constitute a major part of the discipline of volcanotectonics.

Volcanotectonics in 2030

Data and insights of great value to the further development of volcanotectonics have recently been obtained from petrological/geochemical studies. These include studies of deep-seated transcrustal magmatic systems (Cashman et al. 2017), the eruption timescales and dynamics (e.g. Dingwell 1996; Caricchi et al. 2007; Druitt et al. 2012; Lavallée et al. 2015; Viccaro et al. 2016; Flaherty et al. 2018; Ruth et al. 2018), the pre-eruptive storage conditions of the eruptive magma (e.g., Cadoux et al. 2014; Putirka 2017; Stock et al. 2018; Humphreys et al. 2021) and the petrogenetic evolution of the plumbing systems from their subaerial lavas to pyroclastic products (e.g. Martin et al. 2006; Andújar et al. 2015; Cooper et al. 2019; Buckland et al. 2021).

Volcanotectonics, like other disciplines, embraces technological advances such as new generations of high-resolution satellite systems with free data access (e.g. the 8 satellites of the EU's Earth Observation Programme Copernicus), data collection from UAV (drone) surveys, innovative and machine-learning supported data analysis (Bueno et al. 2019), as well as virtual reality applications (Fig. 2; Tibaldi et al. 2020; Bonali et al. 2021). In this decade, many of these techniques will further allow remote monitoring of volcanoes and hence permit a greater volume of data to be acquired with larger temporal resolution. The use of low-cost technologies such as fibre optic cables have the potential to expand greatly the spatial coverage of strain and seismic data at volcanoes, and the accuracy of these data will improve as the techniques develop (Jousset et al. 2018; Currenti et al. 2021). Machine learning methods will be used to better distinguish data from noise and to improve the forecasting of volcano behaviour, including the accumulation of stress, strain and energy, in near or actual real-time, in and around volcanoes.

A great challenge, but a reasonable goal, in this decade is to provide a robust theoretical framework that allows for a realistic interpretation of the various geophysical signals during unrest periods. To do so requires as complete an understanding as possible of the underlying geology and structures within and around a volcano, and so detailed geological field studies remain paramount. It is now understood that the orientation and arrangement, as well as the mechanical properties, of the units/layers that constitute a volcano can substantially alter recorded surface deformation fields (Bazargan and Gudmundsson 2019; Clunes et al. 2021), and may generate substantial error if an elastic half-space is assumed (Masterlark 2007; Gudmundsson 2020). In addition to well-known and long-studied earthquake swarms and deformation signals, some volcanoes provide thermal signals that may appear years or decades before eruptions (Girona et al. 2021). These signals need to be linked with thermo-mechanical deformation processes that lead to seismogenic rock failure (Browning et al. 2021). The potential effects of earthquakes, particularly large ones, on nearby volcanoes need to be further explored (Manga and Brodsky 2006; Namiki et al. 2016; Seropian et al. 2021). Since most dike/sheet injections do not result in eruptions (Gudmundsson 2020), a more fruitful approach might be to look for evidence of earthquake-triggered dike/sheet injections rather than eruptions. Advances in muography, magnetotelluric and gravimetric techniques will allow further constraints on volcanotectonic structures that can be linked to field measurements (Athanassas 2020; Pearce et al. 2020; Okubo 2020). Also, global satellite-measured precipitation will help to understand how infiltrated rain/ground water affect volcanoes under unrest (Farquharson and Amelung 2020).

Most volcanic eruptions occur because a magma-filled fracture (dike/sheet) is able to propagate from its source to the surface. Magma-source rupture and propagation of the resulting fracture to the surface are primarily controlled by physical principles derived from fluid and solid (including fracture) mechanics, analytical mechanics and thermodynamics/statistical physics (Gudmundsson 2020). Key issues here are the strain energy that accumulates in the volcano during unrest before magma-source rupture and the local stresses in, and the mechanical properties of, the layers between the source and the surface. Novel laboratory studies will be required to constrain the evolution of the in situ and upscaled rock properties (Heap et al. 2020; Heap and Violay 2021). The strain accumulation provides much of the energy needed to form and propagate the magma-filled fracture, and the local stresses, to a large degree, determine whether or not the fracture is able to reach the surface to supply magma to an eruption.

In conclusion, the decade will see much more focus on understanding the physics of volcanoes. That understanding, combined with geological and geophysical fieldwork and modelling, should bring us closer to the goal of reliable forecasting of the time, place and size of volcanic eruptions.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00445-022-01582-4.

Acknowledgements We thank the journal reviewers for helpful comments. K. Drymoni acknowledges a Progetto di Eccellenza fellowship from the Italian Ministry of University and Research. J. Browning acknowledges support from Fondecyt 11190143. M.J. Heap acknowledges support from the Institut Universitaire de France (IUF).

Funding Open access funding provided by Università degli Studi di Milano - Bicocca within the CRUI-CARE Agreement.

References

Acocella V (2007) Understanding caldera structure and development: an overview of analogue models compared to natural calderas. Earth Sci Rev 85:125–160

Acocella V (2021) Volcano-tectonic processes. Advances in Volcanology. Springer-Nature, Heidelberg

Adams FD (1938) The birth and development of the geological sciences. Williams & Wilkins, Baltimore

Agustsdottir T, Woods J, Greenfield T, Green RG, White RS, Winder T, Brandsdóttir B, Steinthórsson S, Soosalu H (2016) Strike-slip faulting during the 2014 Bárðarbunga-Holuhraun dike intrusion, central Iceland. Geophys Res Lett 43:1495–1503

Athanassas CD (2020) Muography for geological hazard assessment in the South Aegean active volcanic arc (SAAVA). Med Geosc Rev 2:233–246

Anderson EM (1905) The dynamics of faulting. Edinburgh Geol Soc Trans 8:387–402

Anderson EM (1936) The dynamics of formation of cone-sheets, ring-dykes, and caldron-subsidences. Proceedings of the Royal Society Edinburgh 56:128–157

Anderson EM (1951) Dynamics of faulting and dyke formation, 2nd edn. Olivier and Boyd, Edinburgh

Anderson KR, Johanson IA, Patrick MR, Gu M, Segall P, Poland MP, Montgomery-Brown EK, Miklius M (2019) Magma reservoir failure and the onset of caldera collapse at Kīlauea Volcano in 2018. Science 366:6470

Andújar J, Scaillet B, Pichavant M, Druitt TH (2015) Differentiation conditions of a basaltic magma from Santorini and its bearing on basalt–andesite to andesite magma production in arc settings. J Petrol 56:765–794

Bazargan M, Gudmundsson A (2019) Dike-induced stresses and displacements in layered volcanic zones. J Volcanol Geoth Res 384:189–205

Bueno A, Benitez C, De Angelis S, Moreno AD, Ibanez JM (2019) Volcano-seismic transfer learning and uncertainty quantification with Bayesian neural networks. IEEE Trans Geosci Remote Sens 58:892–902

Bosworth W, Burke K, Strecker M (2003) Effect of stress fields on magma chamber stability and the formation of collapse calderas. Tectonics 22:4. https://doi.org/10.1029/2002TC001369

Bonali FL, Corti N, Russo E, Marchese F, Fallati L, Mariotto FP, Tibaldi A (2021) Commercial-UAV-based structure from motion for geological and geohazard studies. Building knowledge for geohazard assessment and management in the Caucasus and other orogenic regions. Springer, Heidelberg, pp 389–427

Browning J, Drymoni K, Gudmundsson A (2015) Forecasting magma-chamber rupture at Santorini volcano, Greece. Scientific Reports 5. https://doi.org/10.1038/srep15785

Browning J, Karaoğlu Ö, Bayer Ö, Turgay MB, Acocella V (2021) Stress fields around magma chambers influenced by elastic thermo-mechanical deformation: implications for forecasting chamber failure. Bull Volcanol 83. https://doi.org/10.1007/s00445-021-01471-2

Buckland HM, Saxby J, Roche M, Meredith P, Rust AC, Cashman KV, Engwell SL (2021) Measuring the size of non-spherical particles and the implications for grain size analysis in volcanology. J Volcanol Geoth Res 415:107257

Cadoux A, Scaillet B, Druitt TH, Deloule E (2014) Magma storage conditions of large Plinian eruptions of Santorini Volcano (Greece). J Petrol 55:1129–1171

Caricchi L, Burlini L, Ulmer P, Gerya T, Vassalli M, Papale P (2007) Non-Newtonian rheology of crystal-bearing magmas and implications for magma ascent dynamics. Earth Planet Sci Lett 264:402–419

Cashman KV, Sparks RSJ, Blundy J (2017) Vertically extensive and unstable magmatic systems: a unified view of igneous processes. Science 355:6331

Caudron C, Taisne B, Kugaenko Y, Saltykov V (2015) Magma migration at the onset of the 2012–13 Tolbachik eruption revealed by seismic amplitude ratio analysis. J Volcanol Geoth Res 307:60–67

Chaussard E, Amelung F (2014) Regional controls on magma ascent and storage in volcanic arcs. Geochemistry, Geophysics, Geosystems 15. https://doi.org/10.1002/2013GC005216

Clunes M, Browning J, Cembrano J, Marquardt C, Gudmundsson A (2021) Crustal folds alter local stress fields as demonstrated by magma sheet—fold interactions in the Central Andes. Earth Planet Sci Lett 570:117080

Cooper GF, Blundy JD, Macpherson CG, Humphreys MC, Davidson JP (2019) Evidence from plutonic xenoliths for magma differentiation, mixing and storage in a volatile-rich crystal mush beneath St. Eustatius, Lesser Antilles. Contributions to Mineralogy and Petrology 174(5):39

Currenti G, Jousset P, Napoli R, Krawczyk R, Weber M (2021) On the comparison of strain measurements from fibre optics with a dense seismometer array at Etna volcano (Italy). Solid Earth 12:993–1003

Davis T, Bagnardi M, Lundgren P, Rivalta E (2021) Extreme curvature of shallow magma pathways controlled by competing stresses: insights from the 2018 Sierra Negra eruption. Geophysical Research Letters 48. https://doi.org/10.1029/2021GL093038

Dingwell DB (1996) Volcanic dilemma: flow or blow? Science 273:1054–1055

Druitt T, Costa F, Deloule E et al (2012) Decadal to monthly timescales of magma transfer and reservoir growth at a caldera volcano. Nature 482:77–80

Drymoni K, Browning J, Gudmundsson A (2020) Dyke-arrest scenarios in extensional regimes: insights from field observations and numerical models, Santorini, Greece. J Volcanol Geoth Res 396:106854

Drymoni K, Browning J, Gudmundsson A (2021) Volcanotectonic interactions between inclined sheets, dykes, and faults at the Santorini Volcano, Greece. J Volcanol Geotherm Res 416. https://doi.org/10.1016/j.jvolgeores.2021.107294

Dzurisin D (2006) Volcano deformation: new geodetic monitoring techniques. Springer Verlag, Heidelberg

Farquharson JI, Amelung F (2020) Extreme rainfall triggered the 2018 rift eruption at Kīlauea Volcano. Nature 580:491–495

Fedotov SA, Chirkov AM, Gusev NA, Kovalev GN, Slezin YB (1980) The large fissure eruption in the region of Plosky Tolbachik volcano in Kamchatka, 1975–1976. Bulletin Volcanologique 43:47–60

Flaherty T, Druitt TH, Tuffen H, Higgins MD, Costa F, Cadoux A (2018) Multiple timescale constraints for high-flux magma chamber assembly prior to the Late Bronze Age eruption of Santorini (Greece). Contrib Miner Petrol 173:75

Geikie A (1897) The ancient volcanoes of Great Britain, vol 2. Macmillan, London

Geikie A (1905) The founders of geology, 2nd edn. Macmillan, London

Geshi N, Shimano T, Chiba T, Nakada S (2002) Caldera collapse during the 2000 eruption of Miyakejima volcano, Japan. Bull Volcanol 64:55–68

Geshi N, Browning J, Kusumoto S (2020) Magmatic overpressures, volatile exsolution and potential explosivity of fissure eruptions inferred via dike aspect ratios. Sci Rep 10:1–9

Geyer A, Marti J (2008) The new worldwide collapse caldera database (CCDB): a tool for studying and understanding caldera processes. J Volcanol Geoth Res 175:334–354

Geyer A, Marti J (2014) A short review of our current understanding of the development of ring faults during collapse caldera formation. Frontiers in Earth Sciences 2:22. https://doi.org/10.3389/feart.2014.00022

Gilbert GK (1877) Geology of the Henry Mountains. U.S Geographical and Geological Survey of the Rocky Mountain Region, Washington

Girona T, Realmuto V, Lundgren P (2021) Large-scale thermal unrest of volcanoes for years prior to eruption. Nat Geosci 14:238–241

Gudmundsson A (2011) Rock fractures in geological processes. Cambridge University Press, Cambridge

Gudmundsson A (2020) Volcanotectonics. Understanding the structure, deformation and dynamics of volcanoes. Cambridge University Press, Cambridge

Heap MJ, Villeneuve M, Albino F, Farquharson JI, Brothelande W, Amelung F, Got JL, Baud P (2020) Towards more realistic values of elastic moduli for volcano modelling. Journal of Volcanology and Geothermal Research 390. https://doi.org/10.1016/j.jvolgeores.2019.106684

Heap MJ, Violay ME (2021) The mechanical behaviour and failure modes of volcanic rocks: a review. Bull Volcanol 83:1–47

Hubbert MK, Willis DG (1957) Mechanics of hydraulic fracturing. Petroleum Transactions of the AIME 210:153–168

Humphreys MCS, Smith VC, Coumans JP, Riker JM, Stock MJ, de Hoog JCM, Brooker RA (2021) Rapid pre-eruptive mush reorganisation and atmospheric volatile emissions from the 12.9 ka Laacher See eruption, determined using apatite. Earth Planet Sci Lett 576:117198

Inglis CE (1913) Stresses in a plate due to the presence of cracks and sharp corners. Transactions of the Institute of Naval Architects 55:219–230

Jousset P, Reinsch T, Ryberg T, Blanck H, Clarke A, Aghayev R, Hersir GP, Henninges J, Weber M, Krawczyk CM (2018) Dynamic strain determination using fibre-optic cables allows imaging of seismological and structural features. Nat Commun 9:1–11

Kinvig HS, Geyer A, Gottsmann J (2009) On the effect of crustal layering on ring-fault initiation and the formation of collapse calderas. J Volcanol Geoth Res 186(3–4):293–304

Lavallée Y, Stix J, Kennedy B, Richer M, Longpre MA (2004) Caldera subsidence in areas of variable topographic relief: results from analogue modeling. J Volcanol Geoth Res 129:219–236

Lavallée Y, Wadsworth FB, Vasseur J, Russell JK, Andrews GDM, Hess K-U, von Aulock FW, Kendrick JE, Tuffen H, Biggin AJ, Dingwell DB (2015) Eruption and emplacement timescales of ignimbrite super-eruptions from thermo-kinetics of glass shards. Front Earth Sci 3:2. https://doi.org/10.3389/feart.2015.00002

Manconi A, Walter TR, Amelung F (2007) Effects of mechanical layering on volcano deformation. Geophys J Int 170:952–958

Manga M, Brodsky EE (2006) Seismic triggering of eruptions in the far field: volcanoes and geysers. Annu Rev Earth Planet Sci 34:263–291

Marti J, Lopez C, Bartolini S, Becerril L, Geyer A (2016) Stress controls of monogenetic volcanism: a review. Frontiers of Earth Sciences 4:106. https://doi.org/10.3389/feart.2016.00106

Martin VM, Holness MB, Pyle DM (2006) Textural analysis of magmatic enclaves from the Kameni Islands, Santorini. Greece J Volcanol Geotherm Res 154:89–102

Masterlark T (2007) Magma intrusion and deformation predictions: sensitivities to the Mogi assumptions. Journal of Geophysical Research: Solid Earth 112:B6

Melan E (1932) Der Spannungszustand der durch eine Einzelkraft im Innern beanspruchten Halbscheibe (Point force at internal point in a semi-infinite plate). Z Angew Math Mech 12:343–346

Michel J, Baumgartner L, Putlitz B, Schaltegger U, Ovtcharova M (2008) Incremental growth of the Patagonian Torres del Paine laccolith over 90 k.y. Geology 36:459–462

Mindlin RD (1936) Force at a point in the interior of a semi-infinite solid. Physics 7:195–202

Mogi K (1958) Relations between the eruptions of various volcanoes and the deformation of the ground surfaces around them. Bulletin of Earth Research Institute of University of Tokyo 36:99–134

Namiki A, Rivalta E, Woith H, Walter TR (2016) Sloshing of a bubbly magma reservoir as a mechanism of triggered eruptions. J Volcanol Geoth Res 320:156–171

Okada Y (1985) Surface deformation due to shear and tensile faults in a half-space. Bull Seismol Soc Am 75:1135–1154

Okada Y (1992) Internal deformation due to shear and tensile faults in a half-space. Bull Seismol Soc Am 82:1018–1040

Okubo S (2020) Advances in gravity analyses for studying volcanoes and earthquakes. Proc Jpn Acad B96:50–69. https://doi.org/10.2183/pjab.96.005

Passarelli L, Rivalta E, Cesca S, Aoki Y (2015) Stress changes, focal mechanisms, and earthquake scaling laws for the 2000 dike at Miyakejima (Japan). J Geophys Res 120:4130–4145

Pearce RK, Sánchez de la Muela A, Moorkamp M, Hammond JO, Mitchell TM, Cembrano J, Araya Vargas J, Meredith PG, Iturrieta P, Perez-Estay N, Marshall NR (2020) Reactivation of fault systems by compartmentalized hydrothermal fluids in the Southern Andes revealed by magnetotelluric and seismic data. Tectonics 39. https://doi.org/10.1029/2019TC005997

Phillips WJ (1974) The dynamic emplacement of cone sheets. Tectonophysics 24:699–784

Pollard DD, Holzhausen G (1979) On the mechanical interaction between a fluid-filled fracture and the earth's surface. Tectonophysics 53:27–57

Pollard DD, Fletcher RC (2005) Fundamentals of structural geology. Cambridge University Press, Cambridge

Press F (1965) Displacements, strains, and tilts at teleseismic distances. J Geophys Res 70:2395–2412

Putirka K (2017) Down the crater: where magmas are stored and why they erupt. Elements 13:11–16

Rivalta E, Taisne B, Bunger AP, Katz RF (2015) A review of mechanical models of dike propagation: schools of thought, results and future directions. Tectonophysics 638:1–42

Rivalta E, Corbi F, Passarelli L, Acocella V, Davis T, Di Vito MA (2019) Stress inversions to forecast magma pathways and eruptive vent location. Sci Adv 5:9784

Robson GR, Barr KG (1964) The effect of stress on faulting and minor intrusions in the vicinity of a magma body. Bull Volcanol 27:315–330

Roman DC, Cashman KV (2018) Top–down precursory volcanic seismicity: Implications for 'stealth' magma ascent and long-term eruption forecasting. Frontiers in Earth Science 6. https://doi.org/10.3389/feart.2018.00124

Roche O, Druitt TH, Merle O (2000) Experimental study of caldera formation. J Geophys Res 105:395–416

Ruth DC, Costa F, De Maisonneuve CB, Franco L, Cortés JA, Calder ES (2018) Crystal and melt inclusion timescales reveal the evolution of magma migration before eruption. Nat Commun 9(1):1–9

Segall P (2010) Earthquake and volcano deformation. Princeton, Princeton University Press

Segall P, Anderson K (2021) Repeating caldera collapse events constrain fault friction at the kilometer scale. Proc Natl Acad Sci 118:30

Seropian G, Kennedy BM, Walter TR, Ichihara M, Jolly AD (2021) A review framework of how earthquakes trigger volcanic eruptions. Nature Communication 12. https://doi.org/10.1038/s41467-021-21166-8

Steketee JA (1958a) On Volterra's dislocations in a semi-infinite elastic medium. Can J Phys 36:192–205

Steketee JA (1958b) Some geophysical applications of the elasticity theory of dislocation. Can J Phys 36:1168–1198

Stock MJ, Humphreys MC, Smith V, Isaia R, Brooker RA, Pyle DM (2018) Tracking volatile behaviour in sub-volcanic plumbing systems using apatite and glass: insights into pre-eruptive processes at Campi Flegrei. Italy Journal of Petrology 59(12):2463–2492

Sparks RSJ (2003) Forecasting volcanic eruptions. Earth Planet Sci Lett 210:1–15

Sturkell E, Ágústsson K, Linde AT, Sacks SI, Einarsson P, Sigmundsson F, Geirsson H, Pedersen R, LaFemina PC, Olafsson H (2013) New insights into volcanic activity from strain and other deformation data for the Hekla 2000 eruption. J Volcanol Geoth Res 256:78–86

Tepp G (2021) Material failure and caldera collapse: insights from the 2018 Kilauea eruption. Earth Planet Sci Lett 553:116621

Tibaldi A, Bonali FL, Vitello F, Delage E, Nomikou P, Antoniou V, Becciani U, Wyk V, de Vries B, Krokos M, Whitworth M (2020) Real world–based immersive virtual reality for research, teaching and communication in volcanology. Bull Volcanol 82:1–12

Viccaro M, Giuffrida M, Nicotra E, Cristofolini R (2016) Timescales of magma storage and migration recorded by olivine crystals in basalts of the March–April 2010 eruption at Eyjafjallajökull volcano. Iceland American Mineralogist 101(1):222–230

Wilson LG (1998) Lyell: the man and his times. In: Blundell DJ, Scott AC (eds) Lyell: the past is the key to the present. Geological Society of London Special Publication 143:21–37

Authors and Affiliations

Agust Gudmundsson[1] · Kyriaki Drymoni[2] · John Browning[3] · Valerio Acocella[4] · Falk Amelung[5] · Fabio L. Bonali[2] · Abdelsalam Elshaafi[6] · Ines Galindo[7] · Nobuo Geshi[8] · Adelina Geyer[9] · Michael J. Heap[10,11] · Özgür Karaoğlu[12] · Shigekazu Kusumoto[13] · Joan Marti[9] · Virginie Pinel[14] · Alessandro Tibaldi[2] · Thorvaldur Thordarson[15] · Thomas R. Walter[16]

[1] Department of Earth Sciences, Royal Holloway University of London, Egham, UK

[2] Department of Earth and Environmental Sciences, University of Milan-Bicocca, 20126 Milan, Italy

[3] Faculty of Engineering, Pontificia Universidad Católica de Chile, Santiago, Chile

[4] Dipartimento Di Scienze, Università Roma Tre, Rome, Italy

[5] Department of Marine Geosciences, University of Miami, 4600 Rickenbacker Causeway, Miami, FL, USA

[6] Department of Earth Sciences, Faculty of Science, University of Benghazi, Benghazi, Libya

[7] Spanish Geological Survey, Canary Unit, Las Palmas de Gran Canaria, Spain

[8] Geological Survey of Japan, AIST, Tsukuba, Japan

[9] Geosciences Barcelona, CSIC, Barcelona, Spain

[10] Institut Terre Et Environnement de Strasbourg, UMR 7063, Université de Strasbourg, CNRS, 5 rue René Descartes, 67084 Strasbourg, France

[11] Institut Universitaire de France (IUF), 1 rue Descartes, 75231 Paris, France

[12] Department of Geological Engineering, Eskişehir Osmangazi University, 26040 Eskişehir, Turkey

[13] Institute for Geothermal Sciences, Kyoto University, 3088-176 Noguchibaru, Beppu, Oita 874-0903, Japan

[14] University Grenoble Alpes, University Savoie Mont Blanc, CNRS, IRD, UGE, ISTerre, Grenoble, France

[15] Faculty of Earth Sciences, University of Iceland, Reykjavik, Iceland

[16] GFZ German Research Centre for Geosciences, 14473 Potsdam, Telegrafenberg, Germany