Chapter 3.2. Distributed Volcanic fields

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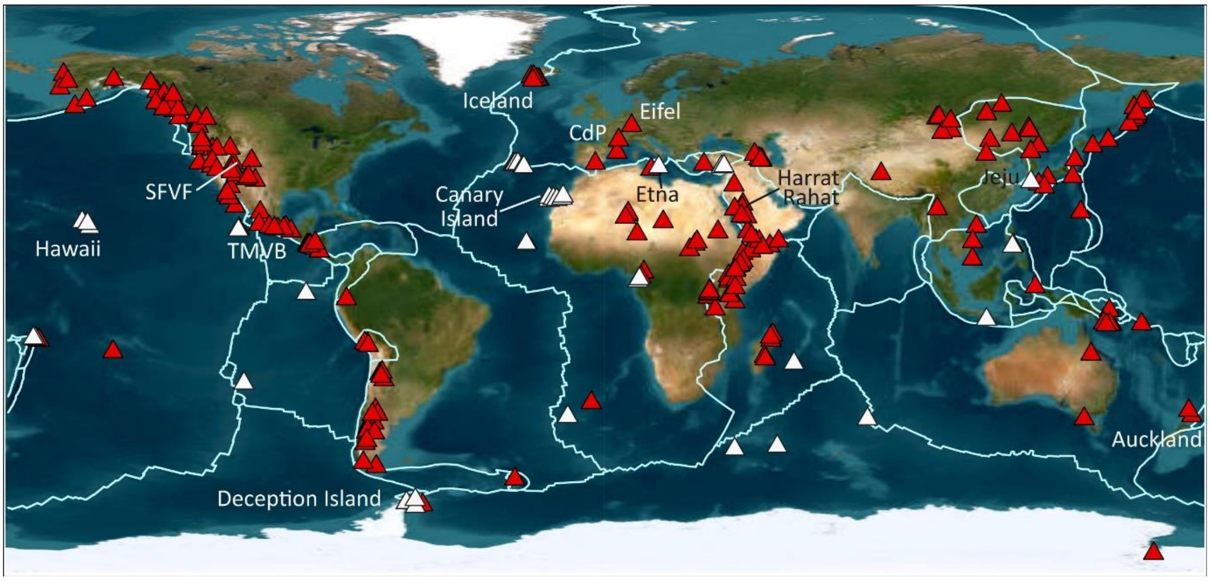
Abstract: Distributed volcanic fields are typically low magma-flux systems, and occur in every tectonic setting. Their volcanoes are typically but not exclusively small-volume (≤1 km^3 of magma). The most typical type of volcanoes associated with volcanic fields include scoria cones, tuff rings, maars, tuff cones, spatter cones, and associated lava flows, in addition to sparse medium-size shields and lava domes. Volcanic fields have spatial extents up to 10,000s km^2 and in places overlap with major cities and critical infrastructure. This chapter gives an up-to-date overview on research into the geology, geochemistry and geophysics of volcanic fields, highlighting the typical physico-chemical processes responsible for their spatio-temporal evolution and associated hazards.

Key words: scoria cone, maar, tuff ring, volcanic field, magma batch, monogenetic, lava domes, volcanic hazard

Introduction

Distributed volcanic fields are a kind of volcanic system found in every tectonic setting, including along divergent, convergent and transform plate boundaries, as well as in intraplate settings (Figure 3.2.1). Distributed volcanic fields can be defined as areas of scattered volcanic edifices that are individually small in volume (typically but not exclusively ≤1 km^3 Dense Rock Equivalent) and are not directly located on a central-vent composite volcano [1]. The volcanoes making up these fields typically form during a single eruptive episode lasting from days to a decade and are therefore classified as monogenetic [2]. Even though individual edifices are usually short-lived due to limited magma supply, a volcanic field can be active for millions of years, hence longer than many composite volcanoes. Such volcanic activity can, however, vary considerably over time, showing temporal clustering (called flare-up) that are known for many well-dated active volcanic fields, for example at Auckland, New Zealand; San Francisco volcanic field, USA; La Garrotxa, Spain; or in Michoacán–Guanajuato, Mexico.

Eruptive products of distributed volcanic fields are commonly mafic and have traditionally been considered “basaltic”, however, there are many examples ofdepartures towards more evolved compositions induced by compositional evolution over time and by source heterogeneities (Trans-Mexican Volcanic Belt, Arabian volcanic field, Dunedin Volcanic Group in New Zealand). Great examples of such diversity are the Serdán-Oriental Basin and the Xalapa volcanic fields in Mexico, which are mostly rhyolitic and basaltic in composition, respectively, despite overlapping in time and space. To reflect the compositional diversity, this chapter uses “basaltic” in a broad and compositionally wide definition that captures the geological and geochemical evolution of volcanic fields in a large range of geodynamic contexts.



*** Insert Figure 3.2.1***

Caption: Map showing the locations of distributed volcanic fields (red triangles) and major sites where monogenetic volcanoes formed on in the Holocene, and around larger polygenetic volcanoes (white triangles) based on the Smithsonian Institution Global Volcanism Program Database. Note that the actual number of volcanic fields are larger if Pleistocene volcanic fields are included. Some of the volcanic fields

mentioned in this chapter are indicated. SFVF – San Francisco volcanic field, TMVB – Trans Mexican Volcanic Belt, CdP – Chaîne des Puys.
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Many historic monogenetic eruptions were recorded by eye-witnesses and in some cases by modern volcano monitoring tools. Some well-studied examples are Chinyero (1910, Tenerife Island, Spain), Parícutin (1943-52, Mexico), Nilahue (1955, Chile; now called Carrán), Taal (1965, Philippines), Heimaey (1973, Iceland), Tolbachik (1975-6, Russia), Ukinrek (1977, Alaska), Navidad (1988-9, Chile), Monte Escrivà and Barbagallo (2001-02, Etna, Italy); Okmok (2008, Alaska), Tagoro (2011-12, El Hierro, Spain), Tolbachik (2012-14, Russia), Tajogaite (2021, La Palma Island, Spain). These observations have allowed direct observations to be made on precursor activity (e.g., degassing, deformation, and seismic events) and physical processes leading to the construction of individual volcanoes. The short time scale for construction of a single volcano (days to years) combined with the long-term activity of the field (thousands to millions of years) makes distributed volcanic fields particularly interesting locations for understanding dynamics of magma ascent, and for reconstructing regional tectonic, hydrological, sedimentary, geomorphic and environmental processes.

Some volcanic fields overlap with populations and critical infrastructure. Examples of cities settled in distributed fields include, but are not limited to, Mexico City, Mexico; Auckland, New Zealand; Portland, Oregon; Al-Medinah, Saudi Arabia; and Jeju, South Korea. Naturally, the proximity of volcanic fields to populations has triggered much research to understand the magnitude-frequency distribution, physical processes (e.g., pyroclastic density current, tephra fall) and hazards associated with eruptions. However, a fuller quantitative understanding of both physical processes and hazards from distributed volcanic fields has remained challenging due to their complex spatio-temporal make-up. This chapter gives an up-to-date view on research into their geology, geochemistry and geophysics, which highlights the typical physico-chemical processes responsible for building up distributed volcanic fields.

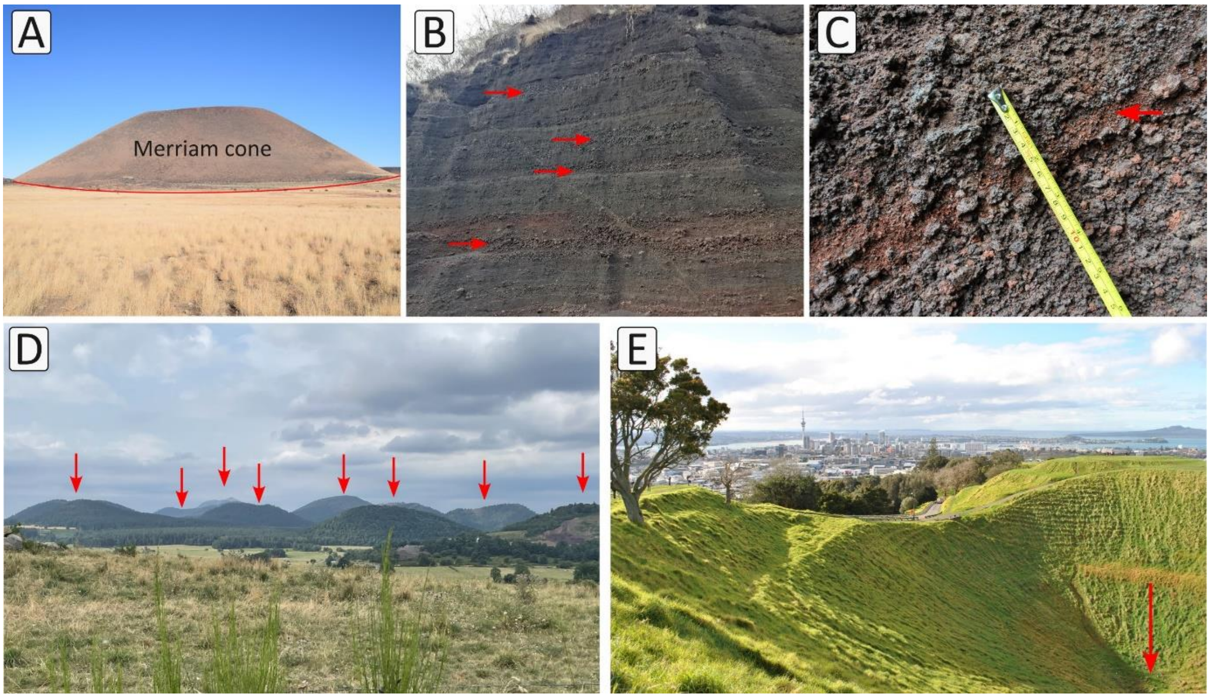
Building blocks of distributed volcanic fields

Distributed volcanic fields consist of a few to thousands of individual volcanoes, scattered over large areas (10s-10,000s km^2). The eruptive history of each individual volcano reflects a dynamic interaction between the environment it erupts into and the magmatic properties (e.g., magma flux, composition). Such interactions can dictate whether during eruption the magma interacts explosively with water (called hydrovolcanic eruptions; see Chapter 'Hydrovolcanism') or it erupts purely due to magmatic volatile exsolution (magmatic eruptions; see Chapter 'Magmatic eruptions'). In both cases, eruptions often form several edifices that are aligned along a direction that coincides with an initial eruptive fissure oriented according to the stress field and/or structural pattern. The diversity of eruption sequences also reflect in the resultant volcano's morphology (see Chapter 'Volcano types and their morphology').

The most common small "magmatic" volcanoes are **scoria cones** (Figure 3.2.2), which outnumber volcanoes of any other type on Earth. While scoria cones appear as simple conical landforms with a crater on top, their eruption sequences can be complex and include multiple distinct eruption styles, including Hawaiian, Strombolian, violent Strombolian and in rare cases, sub-Plinian [3]. These eruptions are driven by exsolved magmatic volatiles, mostly H_2O, CO_2, Cl, F and S, and are controlled by the decompression history of the ascending magma, although there may be intermittent and short-lived magma-water interactions. The depth of fragmentation predominantly stays above ground or at very shallow depth, and thus scoria cones generally contain small proportions of lithic fragments from the country rocks (less than 10 wt.%). Heat transfer during fragmentation by magmatic volatiles creates eruptive columns (up to 20 km in height) from which coarse ash to coarse lapilli particles with occasional blocks and bombs fall and accumulate around the vent [4]. Depending on the production rates and temperature of pyroclasts, some fragments remain hot and fluidal as they land, producing domains of welding and agglutination within the growing scoria cone. These deposits typically form within the crater and along the crater rim during Hawaiian and Strombolian eruptions, forming stacks of erosional-resistant rock. Cones that form on steep pre-eruptive topography are susceptible to flank collapse, resulting in asymmetric edifices with pronounced ramparts.

More energetic eruptions (e.g., violent Strombolian eruptions) produce scoria cones with finer-grained deposits and larger volumes (Figure 3.2.2). In contrast to less explosive eruption styles, the resultant tephra clasts consistently solidify *en-route* to their depositional sites, where they can bounce, roll, or accumulate as a dry, granular medium susceptible to dry granular flows that come to rest at or around the angle of repose. Dry granular flows can be an important transport agent to rapidly remobilize pyroclasts, and form deposits with inversely graded and lenticular beds. Such cones commonly have thin intercalated coarse-ash horizons, representing pulsatory eruption behaviour and intra-eruptive pauses that allow the ash to settle. The proximal deposits transition into a distal tephra blanket dominated by normally graded parallel beds of well-sorted tephra that can cover many hundreds of square kilometres.

Scoria cones are often associated with lava flow(s) fed by volatile-poor magma during the eruption, while there are also examples for clastogenic lava flows that are lava fountain-fed. The lavas can be emplaced at any time during the eruption, however; they tend to be emplaced towards their end and affect potentially large areas (10s-1000s km^2) extending far from the cone and well beyond the tephra blanket (e.g., lavas extend up to 160 km from Kinrara, Toomba, and Undara cones in Queensland, Australia). Lava flows vary between ‘a’a, pahoehoe and blocky types, depending on magma composition and volatile retention, effusion rates, temperature, crystallinity and vesicularity, along with the topography (see Chapter ‘Lava flows, lava lakes, and their hazards’). The emission of lava from within a cone can often produce flank collapses when rafts of the original cone deposits are distributed on top of lava flows, and such collapse events commonly breach the scoria cone craters on one side.



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Caption: Field photos showing the morphological diversity and sedimentological features of scoria cones. (A) Pristine and volumetrically large Merriam cone in San Francisco volcanic field, Arizona has formed through phases of violent Strombolian eruptions; (B) Scoria-dominated succession within a scoria cone in the Xalapa volcanic field, Mexico. Arrows indicate inverse grading due to grain avalanches; (C) Close-up photo of typical scoriaceous lapilli deposits with minor ash horizons (arrow) at Rangitoto volcanoes, Auckland, New Zealand; (D) A row of scoria cones (red arrows) in the Chaîne des Puys, France; (E) View of Auckland downtown, New Zealand, from Mt Eden scoria cone's crater rim. Arrow indicates the crater floor.
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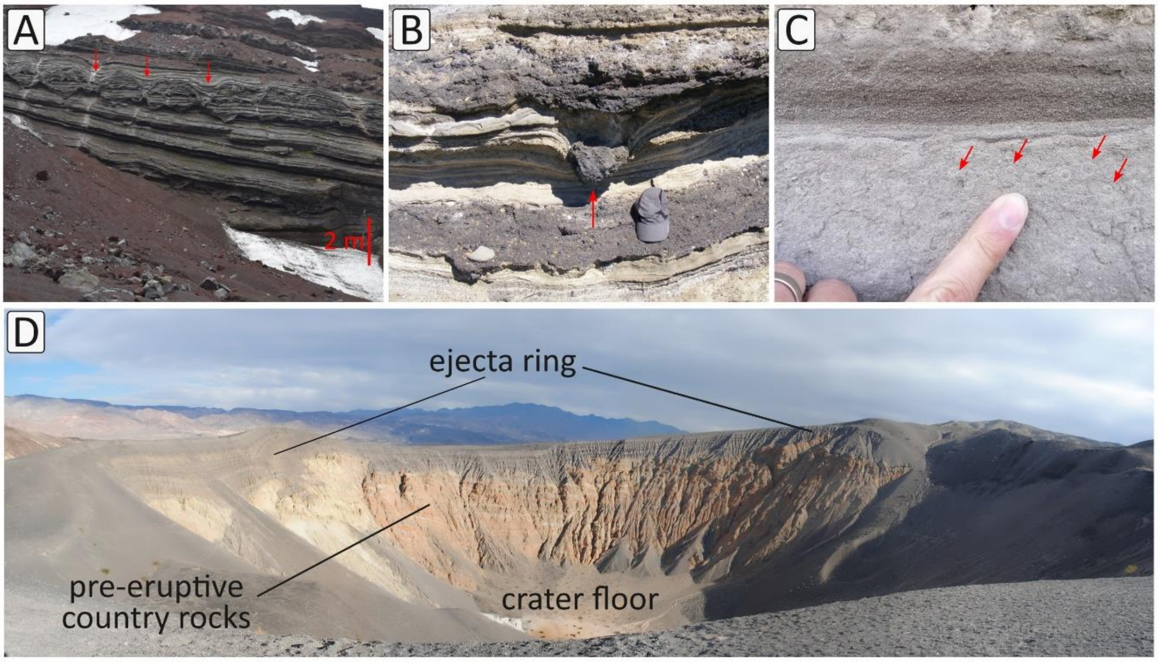
In some distributed volcanic fields, small monogenetic volcanoes co-occur with medium size shield volcanoes and lava domes. **Shield volcanoes** have much larger volumes (>>1 km^3) than most individual monogenetic volcanoes, and they occur with or without a central cone or dome (e.g., Belknap, Oregon). These edifices are often fed by more-evolved magma (e.g., either higher alkali, and/or iron and/or silica content) and can be either monogenetic (e.g., El Metate, Mexico) or, more commonly, polygenetic (Mt. Hallasan, Jeju, South Korea). Polygenetic shields of such large volume require a magma source over an extended period of time (centuries) and are sites of long-lived volcanic activity within a field [5]. The petrogenesis and emplacement processes are more complex than for monogenetic volcanoes and include fractional crystallization at shallow depths in the crust. Further work is required to understand the possible connections (in both space and time) of these volcanoes with surrounding smaller-volume eruptive centres.

Lava domes 0.1 to 10s km^3 in volume and evolved compositions (e.g., dacite, trachyte, rhyolite) erupt when a viscous magma extrudes to the surface forming a circular, steep-side and mound-shaped volcano. They are scattered through many distributed volcanic fields (e.g., Jeju volcanic field, South Korea; Eastern Snake River Plain, USA; Lassen volcanic field, USA; Chaine des Puys, France). They may be associated with shallow magma storage in sills (e.g., Blackfoot, USA) or long-lived complex plumbing systems where storage, crystallization, and crustal assimilation have been occurring for thousands of years, leading to eruptions of hybrid intermediate to felsic magmas in a centralized cluster (Lassen Peak and Chaos Crags, USA). Domes can be surrounded by thick block-and-ash flow deposits formed by collapse of viscous magma during growth, and/or by debris-avalanche deposits from failures caused by hydrothermal or other weakening.

Tuff rings/maars and **tuff cones** form due to the interaction of magma with groundwater and/or standing water [6]. The style of magma-water interaction is a fundamental, though imperfectly understood (see Chapter 'Hydrovolcanism'), control on the fragmentation intensity and in turn on the resultant depositional processes (e.g., pyroclastic density current and fallout dominated sedimentation). The mixing of magma with water or water-bearing sediment can result in explosive fuel-coolant interactions and broadly-speaking 'phreatomagmatic' eruptions. Where magma interacts with glacial meltwater the eruptions can be termed "glaciovolcanic"; such eruptions are common in volcanic fields in British Columbia, Iceland and Antarctica (see Chapter 'Glaciovolcanism').



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Caption: Field photos showing the morphological diversity and sedimentological features of maars and tuff rings. (A) Inward dipping succession of tuff beds at Lake Irizar, Deception Island, Antarctica, Arrows indicate syn-eruptive erosion of the ejecta ring. (B) Impact sag around a ballistic block (arrow) at Motukorea, Auckland volcanic field, New Zealand. (C) Tuff deposits can be rich in spherical aggregates called accretionary lapilli, indicating wet depositional environment at Alchichica, Puebla, Mexico. (D) Overview photo of the Ubehebe crater, USA, that formed through a multi-stage eruption depositing a combination of phreatomagmatic and scoria-dominated sequences.

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Traditionally, the term “tuff rings” refers to phreatomagmatic volcanoes with a crater floor located at or above the pre-existing terrain, while the crater floor of “maars” can be located below pre-existing terrain. This is purely a geomorphic distinction, and it need not reflect any difference in eruption styles, tephra transport or sedimentary features, and thus this chapter refers to them together as maars. **Maars** are characterized by wide (up to a few km), shallow (up to 150-200 m) and semi-circular craters, often formed through amalgamation of multiple smaller craters (Figure 3.2.3). The most studied depositional sequences are within either the ejecta ring (accumulation of pyroclastic deposits around the crater) or within the crater basin exposed after substantial erosion. Ejecta rings consist of alternating fine- to coarse-ash and lapilli-ash deposits and sometime tuff breccias that are thickly to thinly stratified. Deposition is from pyroclastic density currents, ballistic curtains or clasts, and minor fallout from low columns. Depending on their wetness, eruption temperature, and transport mechanism, density-current deposits display a range of bedding (e.g., dune, cross- or planar-bedding), particle types (e.g., accretionary lapilli) and deformation structures (e.g., impact sags). The deposits have substantial (5-90 vol%) lithic contents that are related to the fragmentation and entrainment of the country rocks by shockwaves created by the explosions during crater excavation. Explosions can take place at multiple levels along the feeding dike(s) or within the widening conduit, creating an extensive vertical “pipe” filled with volcanic debris, called a diatreme [7]. Large diatremes can be 2 km deep, host variously fragmented and brecciated deposits sometimes accompanied by economically valuable minerals, such as kimberlite-hosted diamonds and diatreme-hosted epithermal gold-silver deposits.

When external water is abundant and magma supply sufficient, **tuff cones** can form, accumulating an extensive platform/pile of sediment before emerging above the water surface, sometimes then shifting to a magmatic eruption style (e.g., Strombolian). Tuff cones have steeper flanks than ejecta rings of maars, and therefore they resemble scoria cones morphologically. However, they often consist of beds rich in dense- to moderately vesicular juvenile fragments, aggregate particle such as accretionary lapilli, and dominated by grain-avalanche deposits and structures indicative of slumping, sediment deformation, and water escape (Figure 3.2.3). All of these indicate limited aerial transport followed by deposition of damp particles that commonly accumulate to form wet “slurries” on the growing cone flanks. These hyaloclastite-rich deposits of glassy (quenched) clasts are susceptible to rapid post-depositional alteration, forming erosion-resistant orange, yellow to brown deposits of altered glass, called palagonite, which are rich in phyllosilicates and zeolite-group minerals.

A special case of magma-water interaction in volcanic fields takes place during glaciovolcanism which can build **tuyas** that are flat-topped edifices comprising pillow lava and hyaloclastite capped by subaerial lavas (see Chapter ‘Glaciovolcanism’). Tuya morphology is controlled by glacier-magma interactions in areas with extensive current or recent ice-sheet cover, like Canada, Alaska, Iceland and Antarctica. Tuyas and their spatial-temporal distribution can be used to infer paleoenvironmental conditions and reconstruct glaciation histories.

Additional examples and case studies on the geology and eruption styles of small-volume volcanoes are listed in the Further Reading list (QR code).

Short and long-term sedimentary record and their preservation

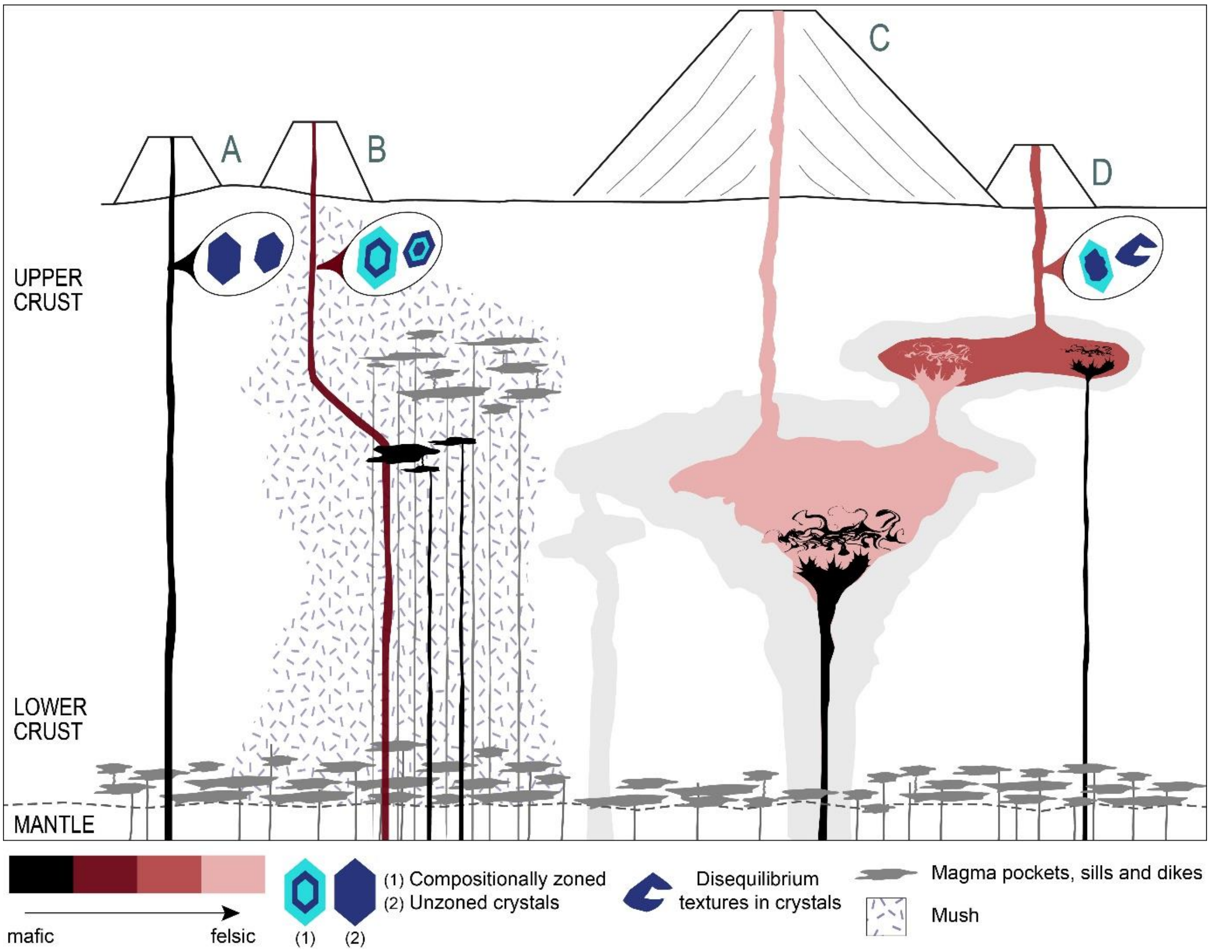
The near-vent deposition of coarse tephra from small-volume eruptions forms a variety of edifices such as scoria cones, maars, and tuff cones. Beyond the edifices themselves, distal areas receive an exponentially thinning tephra blanket that is susceptible to rapid remobilization because the deposits are fine-grained, loose and unconsolidated. Surface deposits of phreatomagmatic volcanoes are usually preserved locally within ~10 km in most cases. Scoria cones disperse their deposits more distally (especially for eruption through violent Strombolian or sub-Plinian eruption styles), but their preservation is ephemeral and patchy. Tephra blankets alter a landscape's permeability, with ash-rich ones in particular temporarily increasing erosion rates; this is especially significant in high-vent density volcanic fields, such as the Pinacate volcanic field or the large Michoacan-Guanajuato volcanic field, both in Mexico. Documented shortly after the Parícutin eruption, loose and unconsolidated ash increased incision and gully development on the neighbouring older scoria cones, and intense rainfall events created lahars. Due to the rapid re-sedimentation and thin deposits, the stratigraphic record of distributed volcanic fields is often heavily biased and sparse.

The individual spatial footprint of proximal deposits is typically less than a few kilometers, but in places tephra >1 cm thick has been deposited as far as 30 km (e.g., Sunset Crater, USA and Parícutin, Mexico) and crypto tephra recognized at 1000 km (e.g., Laacher See, Eifel, Germany). Deposits formed far from the volcanic field can be useful stratigraphic markers for analysis of magmatic, volcanic, and landscape evolution. Distal tephra can be preserved especially well in lakes, and in particular, maar craters that serve as robust local depositional basins [8]. Many maar lakes accumulate nearly continuous successions of annual layers of non-volcanic sediments, called varves, that facilitate dating of intercalated tephra layers from eruptions both within the volcanic fields themselves and from other volcanic systems beyond (e.g., stratovolcanoes nearby). Such depositional systems can record information on time scales of tens to thousands of years, and when combined with isotopic dating techniques, their deposits can help in reconstructing high-resolution, stratigraphically controlled records of climate, habitat, and environmental conditions using the preserved micro- and macro fossils (e.g., pollens, plants, vertebrates and invertebrates). Hence, such sedimentary and biomarker records can contribute to a high-resolution record of past climates, and thereby to understanding future climate variability.

Landscape erosion over millions of years can provide access to all levels of the feeding system, as in fields of Pleistocene to Miocene age (e.g., San Rafael volcanic field, USA; Hopi Buttes volcanic field, USA; and Bakony-Balaton Highland volcanic field, Hungary). Even Mesozoic volcanic fields persist in recognizable form, but without preserving primary edifice morphology. The plumbing of monogenetic volcanoes often consists of either a vertically extended diatreme in the case of a phreatomagmatic volcano, and/or a complex network of sills and dikes in the case of a non-phreatomagmatic volcano. In both cases, the typical deposits preserved subsurface can be very resistant to erosion making these as a good indicator of paleo-topography.

Geochemistry and magmatic system architecture

In distributed volcanic fields, magma commonly travels substantial distances via dikes from the source region, generally in the upper mantle or lower crust, or from mid-crustal intermediate magma storage reservoirs, up to the surface (Figure 3.2.4). Its path is typically roughly vertical; however, there is evidence that magma can also travel significant distances laterally strongly controlled by stress barriers and other discontinuities within the upper lithosphere. For example, during the eruption of Tagoro (2011-12) in El Hierro (Canary Islands, Spain), magma flowed more than 20 km from north to south at 12-15 km beneath the island, the depth of the mantle-crust discontinuity [9]. Once magma generated and accumulated in the mantle reaches the base of the crust or other crustal discontinuities/heterogeneities, depending on its thermal energy, density contrasts, and viscosity, three scenarios are possible: (I) magma becomes part of an underplating process; (II) the dikes are temporarily or permanently stopped (failed eruption) at crustal levels; or (III) ascent continues through the crust culminating in an eruption (Figure 3.2.4). In fact, it is thought that only a small fraction of dikes generated at depth reach the surface, emphasizing the strong control of magma supply, crustal properties and/or stress fields on surface volcanism. Magma batches in distributed volcanic fields ascend through pathways controlled by magma volume and ascent rate (largely buoyancy), the stress field, mechanical layering of the crust, and pre-existing crustal structures. As developed further below, dikes and sills can develop into complex magmatic plumbing system networks.



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Caption: Different crustal scenarios where an intruding dike can reach the surface without significant crustal interaction and carrying unzoned crystals (A), or after interacting with previously emplaced magma batches, potentially part of a transcrustal mush system (B). Progressive accumulation of small batches of mantle magmas (failed eruptions) will condition the path of successive intruding dikes. Crystals record the magmatic interactions as chemical zoning (B). The presence of a central magma chamber (C), where more evolved magmas dominate, will eventually lead to eruptions with intermediate composition resulting from the mixing between intruded dike magma and the crustal evolved reservoirs (D). Based on the interaction degree, different disequilibrium textures and zoning patterns will be found in the crystals.

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Depending on their tectonic and crustal setting, magmas that erupt within a distributed volcanic field may belong to the tholeiitic, calc-alkaline, or alkaline series. Although primitive (basaltic) compositions are the dominant products, some long-lived or more complex systems produce a wide compositional spectrum that extends to felsic compositions (e.g., San Francisco volcanic field, USA), while other fields are truly bimodal with only mafic and felsic magmas (e.g., Harrat Rahat, Saudi Arabia) [10]. Compositional variation is also known within a single eruptive sequence and within a single monogenetic edifice (e.g., Jeju Island in South Korea) [11]. Many arc-related volcanic fields produce more strongly evolved magmas resulting from the interaction of magma with the crust, and persistent delivery of magmas from source to sustained crustal magma bodies (Lassen and Medicine Lake, Cascade Range, USA; San Diego – Cerro Machín Volcano Tectonic Province, Colombia; Chaîne des Puys, France; Eastern Snake River Plain, USA; and Michoacán – Guanajuato volcanic field, Mexico). Eroded volcanic fields expose complex shallow plumbing systems in the form of dikes, sills, and semicircular conduits; the sills can promote chemical differentiation, mixing of magma batches, or crustal assimilation, explaining the wide compositional variability. Melt evolution in shallow storage systems is particularly critical for hazard assessment as evolved melts, potentially enriched in volatiles, may generate unexpected explosive eruptions, as documented at Sunset Crater (San Francisco volcanic field, Arizona) and Tecolote volcano (Pinacate volcanic field, Mexico).

Petrological and geochemical studies provide evidence of the chemical and thermodynamic conditions (i.e., temperature, pressure, and oxygen fugacity) of magma storage and ascent through the crust and identify closed- and open-system magmatic processes. Direct ascent from the magma source, mixing between different magma batches, crustal assimilation, and other open-system processes are recorded by chemical zoning patterns in crystals (Figure 3.2.4). Petrological and geochemical studies of eruptions in distributed volcanic fields have shown that many of their magmas carry multiple populations of crystals as well as crystals with compositional zoning (e.g., Canary Islands, Spain; Eifel volcanic field, Germany; Auckland volcanic field, New Zealand), implying the existence of shallow and probably ephemeral magma reservoirs. Such multi-level crustal systems promote magma differentiation and/or mixing of batches *en-route* to the surface, and the development of transcrustal mush systems (Figure 3.2.4) (see Chapter ‘Intraplate volcanism’).

Chemically zoned element concentrations in minerals such as olivine, plagioclase, and pyroxenes can be used as a chronological tool. The time scales of pre-eruptive processes strongly differ between cases involving direct magma ascent from the mantle source versus those characterized by significant crustal stalling and interaction of magmas with one another or the crust. Parícutin volcano, Mexico, exemplifies direct ascent, showing no evidence of magma mixing during the eruption and with constant magma intrusion/system replenishment. Diffusion chronology in olivine reveals magma-rise time scales of ca. 1.4 days for the early erupted tephra, with a magma ascent rate of 0.08 m s^{-1} (assuming a 10 km depth for dike propagation) [12]. On the other end of the spectrum, there are cases with evidence of multiple mixing events, such as those observed at fields with low volcanic fluxes. There, diffusion modelling of crystal compositional zoning confirms the presence of magma pockets stalled at various crustal levels, interacting over the course of decades, years, months, and days preceding eruption onset [13]. Additional studies on the geochemistry and plumbing development are listed in the Further Reading list (QR code).

Geophysical surveys in volcanic fields

Geophysical studies provide insights into the subsurface architecture of volcanic fields, allowing to examine the internal structure of individual volcanoes and the relationship with local tectonics. At the edifice scale, these indirect methods (including, magnetometry, self-potential, gravimetry, and electrical resistivity tomography) may reveal variations of eruption styles (e.g., deposits with magmatic or phreatomagmatic origin) and the geometry and volume of deposits [14]. These methods are particularly important since the complete volcanic successions are often buried and can only be reconstructed using limited surface outcrops and drill core data (if available). This is particularly important for maars where the largest part of the volcanoes (diatreme) is located underground. Furthermore, methods such as gravity, magnetics, muography and ground penetrating radar have revealed shallow diatreme structures and density variation related to welding/agglutination, and feeder dikes within scoria cones. The results from such studies can complement field-based geological observations, highlighting the shallow volcanic plumbing systems.

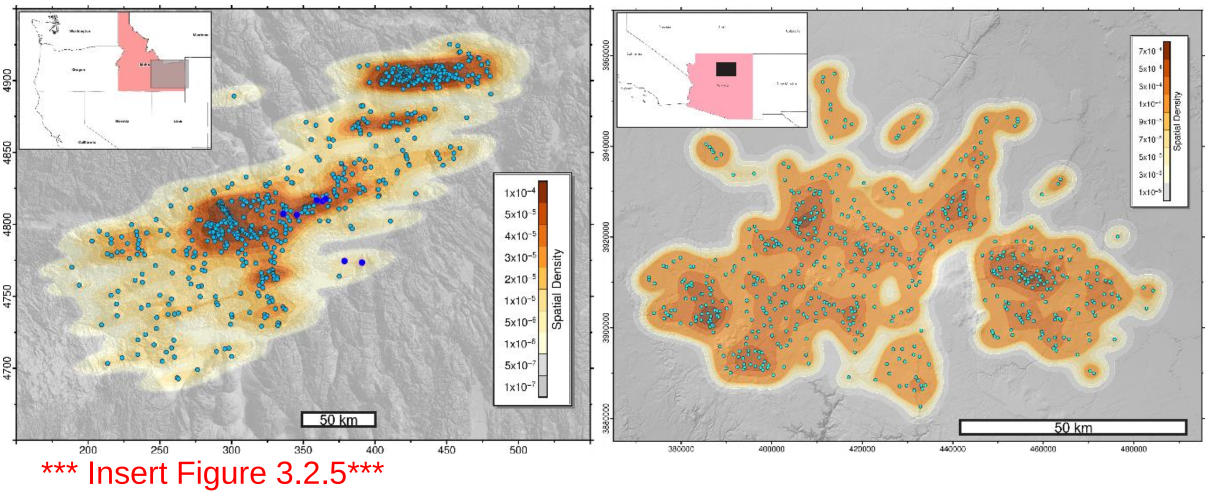
On a volcanic-field scale, geophysical methods can enhance our understanding of how substrate properties and shallow structural features (e.g., fault zone) can control eruptive dynamics. Gravity, magnetic, self-potential, and resistivity methods (e.g. magnetotellurics, electric resistivity tomography and induced polarization) enable the detection of variations in density, magnetic susceptibility, and electrical conductivity, which can indicate the presence of intrusive bodies, hydrothermal alteration zones associated with intrusions, and fault zones.

Seismic, geodetic, and geomagnetic data also play crucial roles in monitoring magmatic processes within a distributed volcanic field [15]. Seismic data provide real-time information on subsurface movements, offering early indications of potential magmatic intrusions and their location. Geodesy, employing techniques like Global Position System and Interferometric Synthetic Aperture Radar (InSAR), monitors ground deformation, which is essential for detecting precursors to volcanic eruptions if the volume of ascending magma is large enough [16]. Geomagnetic surveys detect changes in magnetic fields induced by magma, providing valuable insights into magma reservoir dynamics. Integration of these methods together with geochemical and geological data enables a comprehensive assessment of volcanic hazards and to formulate effective risk mitigation strategies.

Spatial and temporal evolution

The inherent spatio-temporal evolution of volcanism within distributed volcanic fields can capture the interactions of volcanism with tectonics, crustal dynamics (e.g., stress field) and the environment (e.g., host rock mechanics, hydrology and topography). These collectively help determine volcano locations and eruption styles [17]. Like composite volcanoes, most distributed volcanic fields are characterized by periods of high eruption rates alternating with repose periods of variable durations; thus, they can be highly periodic over time. However, most volcanic fields do not have a complete geochronology that hampers detailed insights into their temporal evolution. In field with detailed geochronology on the other hand the periodic activity has been explained by structural and crustal controls [18]. Some distributed volcanic fields only contain small-volume monogenetic volcanoes scattered across a broad region, whereas, with the development of spatial clusters, other fields may also transition to develop larger shields and major felsic edifices (e.g., Lassen Volcanic Centre, USA).

Vent clustering provides evidence of the processes governing magma generation and ascent. Spatial heterogeneity of vents, in the form of clusters and lineaments, is a common feature in distributed volcanic fields (Figure 3.2.5). The causes of this heterogeneity appear varied and include the influence of structural anisotropies within the crust, other zones of weakness, crustal extension or compression, crustal thickness, and shifts in the locus of magma supply. Clusters of vents can be linked to local increases in heat flux and magma supply rate, as well as the presence of large sills and other intrusive bodies promoting long-lived volcanic activity. In contrast, low rates of magma supply result in eruptions that are clustered in space and time. Magma supply from the source to the surface is small and sporadic, and most of the intruding dikes cool down and no longer favour pathways for the next ascending batch. Consequently, new magma batches en-route to the surface create new pathways, opening new vents at the surface, and contributing to the lateral development of a volcanic field.



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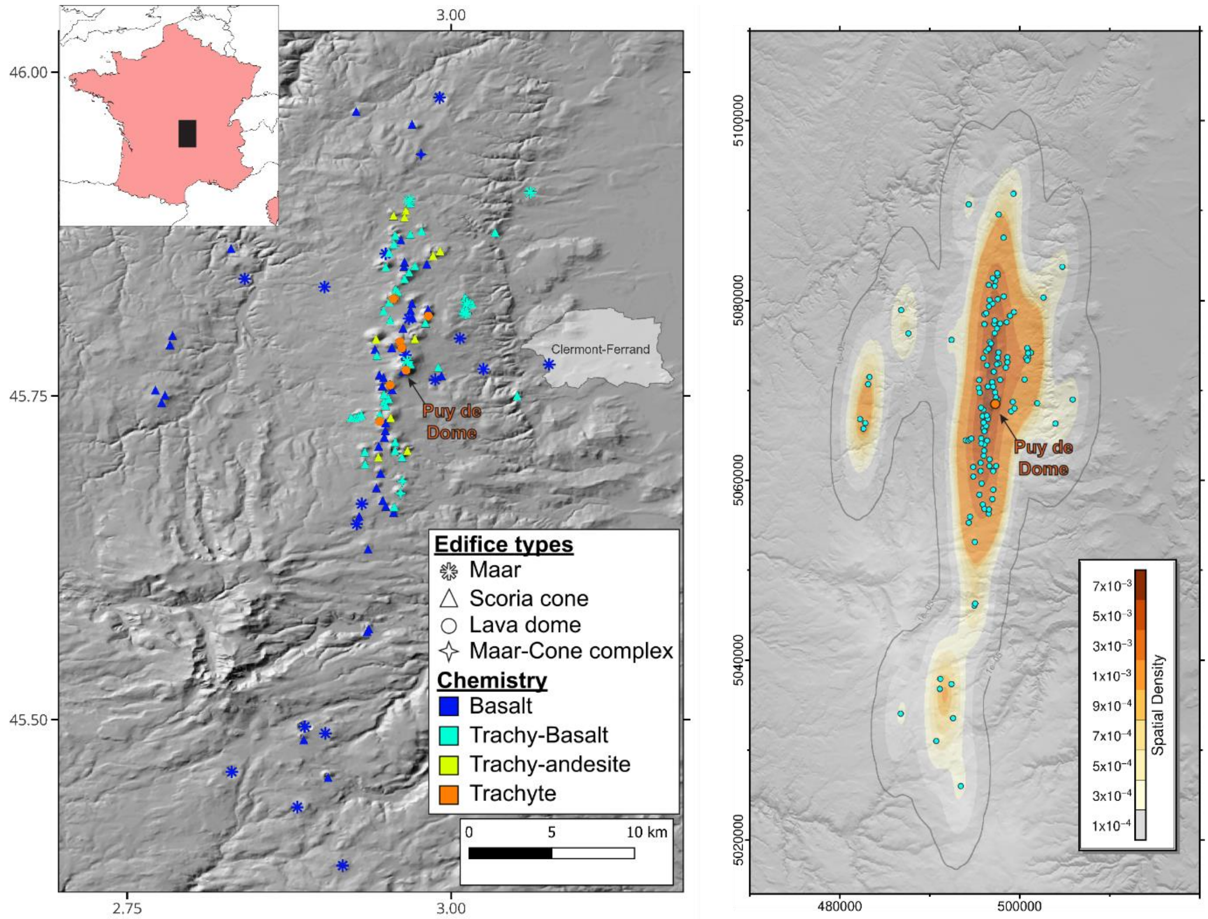
Caption: Spatial density map for (A) the East Snake River Plain (ESRP), Idaho (modified from Connor et al., In Press) and (B) the San Francisco Volcanic Field (SFVF), Arizona using the Gaussian kernel function and log-likelihood bandwidth estimator. Circles represent the location of the Quaternary volcanic vents,. For the ESRP, basaltic vents are in cyan; lava domes are in dark blue. Background is a 30-m digital elevation model (DEM). The map insert shows the location of the study areas (grey box) in south-eastern Idaho and northern Arizona USA. Note the scale bars represent 50 km, highlighting the difference in size of distributed volcanic fields.

Credit: Matthew B. Connor, Laura J. Connor, Chuck B. Connor. *Many Maps are Better Than One: A Random Forest Approach to Estimate Spatial Density in a*

Distributed Volcanic Field, Eastern Snake River Plain (ID). Accepted to Chapman Volume on Distributed Volcanism, U.S. Geological Survey Professional Paper

The geographic boundaries of distributed volcanic fields reflect the extent of the magma source region at depth, and spatial clusters of vents are correlated to preferential pathways that focus the ascent of magma batches. Interestingly, individual volcanoes and clusters spaced kilometers apart and distributed over a volcanic field can be active simultaneously even though not necessarily related to the same magma batch and form chemically district magma batches (Figure 3.2.6).



*** Insert Figure 3.2.6***

Caption: A: Distribution of the Chaine des Puys eruptive vents (<100 ka) by edifice type (scoria cones, domes, maars, and maar-cones) and chemistry of magmas. Basaltic vents are in dark blue, trachy-basalts are in cyan, trachy-andesite are in yellow, and trachyte are in orange. Background is a digital elevation model of the region. UTM coordinates are Zone 31N. The map insert shows the location of the study area (black box) in central France. B: Spatial density map for the Chaine des puys vents using the Gaussian kernel function and log-likelihood bandwidth estimator. Circles represent the location of the volcanic vents.

Credit: -

Statistical analysis of the spatial distribution of eruptive vents is widely used for probabilistic hazard assessment, and particularly to infer where future eruptions may occur [19]. The spatial distribution of vents is generally determined using statistical tests performed to find out whether a set of point-like features is random, clustered, or represented by a Poisson distribution. Spatial density maps are often created to define the geographic limits of a distributed volcanic field, the density of volcanic vents, and to isolate clusters (high vent-density areas). In this view, future eruptions could take place anywhere within the field's limit, with a higher probability close to past clusters of vents, and a lower probability outside of the field's area.

In the same way that we observe spatial clusters, temporal clusters are present in distributed volcanic fields. Volcanic fields are built by eruptions that can be separated in time by decades to millennia. Durations of eruptive versus non-eruptive periods are highly variable due to availability and rate of magma supply. There are multiple methods to calculate Recurrence Rates (RR). One straightforward approach is based on the frequency of volcanic events within a certain timeframe, for example, $RR = (N-1)/(t_0-t_y)$, where N is the total number of eruptions; t_0, the age of the oldest eruption and t_y, the age of the youngest eruption. Because of the spatio-temporal episodicity of distributed volcanic fields, recurrence rates vary in space and time, therefore making it challenging to assess hazards in such fields. Unrelated to the method used, recurrence rates are usually around 10^{-4} to 10^{-6} per year in distributed volcanic fields. For example, $3\text{-}5\times10^{-4}$ vents/year for the Eifel volcanic field (Germany) and Auckland (New Zealand), 1×10^{-5} vents/year in Lunar Crater and Southwest Nevada volcanic fields (USA), and 7.5×10^{-5} in Harrat Rahat (Saudi Arabia).

Analysing and understanding the periods of activity, repose, and unrest in a volcanic field through estimates of recurrence rates is critical to recognizing warning signs prior to volcanic eruptions. Recurrence rate estimates are often employed to anticipate how often volcanic activity can be expected to occur within a given time period. However, due to the dispersed eruptive locations and small volumes of products, there is generally little overlapping of eruptive units, making it hard to establish a complete stratigraphy for an entire volcanic field. Typically, the timing of past activity is established using radiometric dating methods, although the uncertainties inherent to the dating methods may prevent distinction among individual events. Radiometric dating coupled to paleomagnetism allows resolution of some uncertainty and identification of events that were co-eval or distinct. We have not yet reached a stage where it is feasible to conduct hundreds of isotopic age determinations to date most eruptions in a volcanic field. Stratigraphic relationships are limited, and the ones that exist in certain parts of a field are difficult to correlate to other eruptive units several kilometres away, especially in the absence of clear stratigraphic markers, such as regional tephra layers. Morphometric parameters (cone and crater height and width, slope angles) are often used to establish a relative stratigraphy of events. Progressive degradation of the upper parts of cones by erosion, and deposition of the eroded material around their bases, permits quantification of erosional evolution. This allows inference of age for non-dated cones by comparing their morphology to others in the same field with a radiometric date [20].

Because of the spatio-temporal episodicity of distributed volcanic fields, it is challenging to assess whether a field is active or inactive. Most experts would argue that a volcano or volcanic field which has erupted within the Holocene period (<11,650 years ago), has the potential to erupt again in the future, and should be identified as "active". However, the Holocene cutoff is completely arbitrary as numerous volcanic systems can remain dormant for tens of thousands of years before becoming active again. Therefore, if the geological conditions have remained unchanged since the last eruption, then potential for future activity persists. In fact, the Smithsonian's Global

Volcanism Program has expanded its catalogues to include all volcanoes that have erupted as far back as the Pleistocene (<2.6 Ma). This aims to better capture all volcanoes that might still be active. In distributed volcanic fields, the dispersed nature of magmatism implies that some areas may not be revisited by volcanic activity for more than 10,000 years, whereas some clusters may have a higher recurrence rate. It is crucial to pay attention to the characteristics of the volcanic field itself, such as magma-related seismic activity, ground deformation, or an active hydrothermal system. If such observations exist, these provide evidence of the presence of magma in the crust, and the volcanic field should be considered "active" but currently "dormant", regardless of the time since its last eruption.

*** Insert Text Box 3.2.1***

Active distributed volcanic fields: A reflection

According to the USGS (Poland, 2022) or the Smithsonian Institution (Global Volcanism Program, 2024), a volcano or volcanic system is considered active if it has either erupted or experienced a state of unrest in the Holocene (≤11.7 ka). The former defines an active volcano as one that has erupted in the Holocene and hence “has the potential to erupt again” in the future (Szakacs, 1994), while the latter applies the Holocene as a criterion to split the “Volcanoes of the World” database (Siebert et al., 2010). However, the lower bound of the Holocene is defined in ice cores retrieved in the North Greenland Ice Core Project and it corresponds to sharp warming of the climate. This definition is arbitrary from a volcanic or magmatic perspective, as it is based on climatic changes rather than volcanic activity. Therefore, the Holocene cutoff is not a relevant measure for determining whether a volcanic field is active or not. It, in fact, represents only a brief moment in Earth's geological evolution although it is perceived as much longer on a human timescale.

We advocate here that the definition of distributed volcanic fields as active or potentially active should be based on a much more holistic approach, rather than solely considering age of the most recent eruption. The “most recent eruption” approach commonly results in a perception of low volcanic risk and gives a false sense of security to communities located near or within distributed volcanic fields that have not experienced an eruption in historic times. Regardless of their setting, distributed fields tend to erupt infrequently and remain active for hundreds of thousands to millions of years (Németh and Kereszturi, 2015), with repose period often longer than the Holocene epoch. Also, magmas derived from the mantle by partial melting may not erupt to the surface if crustal or surface conditions are unfavourable (e.g., strong compression, thick sedimentary basin fill). An adequate assessment of the activity of a distributed field should take into consideration the total span of volcanic activity, average recurrence interval and whether the geological conditions have remained unchanged since the last eruption. Indications that generation and ascent of magma remains possible, and hence that the field remains alive with potential for future eruptions include the presence of Quaternary volcanoes, which are still geologically young even if pre-Holocene, and/or evidence of an existing magma source from geophysics or geochemistry evidence.

We further recommend conceptualizing this problem as a probability curve, where the longer the repose time the lower the probability for another eruption within a volcanic field. Many examples around the world, including La Garrotxa (Spain), Chaîne des Puys (France), Eifel (Germany), Pinacate (Mexico), Fort Rock (US) among others produced their last eruptions around the Pleistocene-Holocene boundary. Since those and other similar distributed volcanic fields operate on long timescales, the absence of Holocene eruptions does not imply a negligible potential for future eruption. Active volcanism must be defined in a way that captures the true longevity and episodic nature of Earth's volcanism, rather than arbitrarily tied to climate cycles punctuated by glaciation.

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*** Text Box 3.2.1 ends***

Precursor activity and volcanic hazards

Despite continuous research efforts, the combination of deep magma sources, fast magma ascent, unknown sites of eruption, small magma volumes, anthropogenic seismic noise and, generally, lack of instrumental data due to the low recurrence rates of eruptions, severely limit our current ability to interpret monitoring data and identify eruption precursors. Our conceptual models for instrumentation and monitoring are typically adopted from frequently eruptive composite volcanoes (e.g., Piton de la Fournaise, France; Etna, Italy, or Kilauea, USA); this instrumentation is expected to struggle to pick up unrest signals that commonly require cross-correlation of faint signals from the geophysical, geodetic and geochemical monitoring networks. Consequently, the current forecasts are heavily based on statistical analysis of spatio-temporal-volumetric behaviour of the past activity. Despite improved monitoring techniques and enhanced monitoring networks in active volcanic areas, a better knowledge of the eruptive history of distributed volcanic fields and a deeper understanding of the magma plumbing system feeding the eruptions are essential for achieving accurate forecasts and to estimate the unrest time scales.

The hazards and precursors associated with distributed volcanism are as varied as those found at central polygenetic volcanoes, including degassing, seismic activity and ground deformation. However, due to the low recurrence rates of eruptions, not all distributed volcanic fields are consistently monitored, hindering our ability to define universal unrest signatures. The relatively low volumes involved in such eruptions and their rapid onset make it challenging to provide timely warnings to nearby populations with conventional monitoring techniques. To unravel the complexities of distributed volcanic fields and their precursors and hazards, future studies should integrate petrological, geochemical, statistical, numerical, and geological field studies with geophysical investigations.

While individual eruptions may be small, the cumulative impact of multiple simultaneous or successive eruptions or eruptive phases (e.g., fissure-fed eruption with multiple vents) can lead to more significant hazards. The diversity in eruption styles, sizes, and frequencies across the field is also challenging to forecast, especially since uncertainties in the calculation of recurrence rates are relatively high due to the lack of radiometric age determinations for every volcano or eruptive product within a distributed volcanic field. Finally, because eruptions in distributed volcanic fields are less frequent, local communities may be unaware of potential volcanic hazards, impacting preparedness and response measures.

Summary and future directions

Millions of people live within or near distributed volcanic fields, which inherently places critical infrastructure at risk. The large extent of those fields as well as their infrequent volcanic activity, have always made them attractive for human settlements and strong links have been developed between them and the society, through the variety of resources or ecosystem services they provide (e.g., biodiversity, water resources, fertile soils for agriculture, construction material, recreational spaces inspiration for art, opportunities for geotourism and geoeducation). Hence, distributed volcanic fields are key for addressing many United Nations Sustainable Development Goals, such as Goal 11: *Sustainable cities and communities* and Goal 15: *Life On Land*, as well as the United Nation's Sendai Framework for Disaster Risk Reduction. Many countries, however, lack plans to study, monitor, mitigate, and educate about hazards in distributed volcanic fields, despite their great impact on populations and infrastructures. The unpredictable, sporadic nature of volcanic eruptions, their quick onset, and varying intensity were recently observed in La Palma (2021, Spain) and Reykjanes Peninsula (ongoing from 2021, Iceland). It is important in other distributed volcanic fields to assess how long their eruptions last, how far-reaching they are, and the potential impact they could have on nearby densely populated and vulnerable areas before similar eruptions happen. To do so, we need to understand the processes regulating volcanic eruptions, create precise models for them, and utilize the models to predict the scale, duration, and hazards of eruptions in distributed volcanic fields.

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Further Readings

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