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PART 3: Volcanic eruptions and associated products

CHAPTER 2.6 : Volcano stratigraphy and mapping

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Abstract

Volcano-geologic mapping and stratigraphic reconstructions provide important information toward understanding patterns of edifice construction and destruction of volcanic systems, their eruptive histories and recurrence rates, and magmatic evolution and plumbing systems, all of which are required to make informed hazard assessments. Geologic mapping of volcanic terrains also provides context in the search for and identification of natural resources, including geothermal reservoirs and magmatic-related ore deposits, and can provide useful background for communication and outreach. Most volcano-geologic maps and chrono-stratigraphic frameworks are based on a systematic lithostratigraphic approach and are constructed using an iterative process whereby field observations and mapping alternate with acquisition of rock compositional and geochronological data. Modern technological and analytical tools have greatly advanced geochemical and geochronological data acquisition and accuracy, while some technologies have provided new useful tools for fieldwork, including in poorly accessible environments.

Key words

Volcano geology; geologic mapping; eruption history; tephrostratigraphy; volcanic architecture; volcanic successions; volcano tectonics

Introduction

Geologic mapping is essential to understanding Earth's dynamic history. In volcanic terrains, a geologic map is fundamental toward establishing the eruptive history of a whole system and to building a complete time-volume-composition-behavior record that provides the much-needed context for almost all other geological studies of volcanoes. These include petrology and geochemistry for understanding magmatic evolution and plumbing systems [E1], physical volcanology for understanding eruptive and emplacement processes [E2], and distinguishing variable magnitudes, periodicities, and styles of eruption that enhance our understanding of attendant hazards [E3-E4]. A detailed map with a solid chrono-stratigraphic framework provides context for evaluating volcanic and magmatic processes at volcanoes and volcanic fields that change over space and time.

Objectives and use of volcano geologic maps and stratigraphy

A geologic map of a volcano is a graphic representation of a large assemblage of data that includes all that has been learned about its eruptive history. Geologic maps of volcanoes and volcanic fields, combined with robust chrono-stratigraphic frameworks of modern terrains form the basis of key products used in fundamental and applied volcanology research, including at volcano observatories, such as composite lithostratigraphic columns displaying frequency-magnitude relationships of past eruptions and long-term (probabilistic) hazard assessments [E3]. Such assessments ultimately provide inputs for risk assessments and disaster risk reduction [E5]. Ideally, eruption histories from maps and other sources, together with the volcano system models they inform, are used before and during monitoring and crisis response [E6-E7-E8] and serve as a basis for communication and outreach, including communication with the scientific community, government agencies, emergency managers, and/or the general public [E9-E10].

Picturesque landscapes with colorful strata, curious morphologies, and intriguing geologic stories about how and when they formed have led to the establishment of volcano-centered geoheritage sites and increasing volcano tourism (e.g. UNESCO Global Geoparks) [E11-E12]. Such initiatives provide educational opportunities to explain to a broad audience the wider societal benefits of studying volcanoes [E9].

Detailed volcano-structural maps combined with geophysical observations of the shallow subsurface (e.g., resistivity and magneto-telluric surveys) and gas and fluid geochemical analyses (e.g. soil CO_2 flux, fumarole, or hot spring geochemistry) help in building conceptual models of geothermal reservoirs and fluid pathways, and target zones for geothermal exploration and drilling [E13-E14]. In ancient terrains, correct identification of altered volcanogenic deposits might help in assessing potential ore deposits associated with magmatic processes, such as epithermal gold-silver, copper-bearing volcanogenic massive sulfide ores, or diamondiferous kimberlites [E15-E16].

[Additional Reading QR1: "Mapping volcano-related resources"]

Volcanoes are dynamic environments

Volcanic areas are dynamic, whether actively erupting or not. Many geologic processes act on timescales of thousands to millions of years; however, volcanic eruptions and processes can alter landscapes and hydrographic networks over extremely short timeframes (minutes to years). Explosive events can destroy an edifice and, at the same time, provide large amounts of material to surrounding sedimentary environments. Non-eruptive processes such as volcano-edifice collapses can also catastrophically destroy volcanic edifices [E17]. Volcanic deposits can therefore show complex lateral facies variations and contacts at the scale of individual outcrops [1]. Whether by initial emplacement processes or by subsequent reworking, the numerous details of a volcanic history, necessary to provide a sound basis for long-term quantitative hazard assessments, can only be revealed through mapping and stratigraphic reconstruction at adequate spatial and temporal resolutions. A multifaceted approach is therefore needed to produce volcano-geologic maps and to reconstruct volcanic stratigraphy, that include descriptions of each unit, the unit's unique features, and its distribution in the area of interest [1-4].

The progressive and continued development of physical volcanology, and advances in geochronological and geochemical techniques since the 1960s, have generally led to more detailed maps and chrono-stratigraphic reconstructions of volcanic terrains. Modern remote sensing technologies allow for high-resolution digital terrain models, greatly facilitating identification and mapping of large-scale structures and major units that support targeted ground-truthing field campaigns [1, 4].

In this chapter, we introduce the primary methods and approaches used in geologic mapping of volcanoes and stratigraphic reconstruction. We start at the larger scale of the volcano-geologic map, discuss general approaches to fieldwork, and then focus on compiling tephrostratigraphic reconstructions. The mapping and tephrostratigraphy approaches are each illustrated by case studies; together they can be used to reconstruct complete eruptive histories of volcanoes and volcanic fields. We highlight some common challenges and limitations, as well as some recent developments and advances in such field studies.

Methods to carry out volcano stratigraphy and mapping

General principles

Mapping volcanoes and establishing volcanic stratigraphy requires an iterative process. Initial field work that establishes eruptive units distinguished in large part by close examination with a hand lens is corroborated by petrographic, geochemical, paleomagnetic, and geochronologic data, which then inform additional rounds of field and laboratory work. Ultimately, a description of each eruptive unit includes a summary of age, vent site, distribution, lithology, composition, mineralogy, structures, contact relations, and any other characteristics integral to that unit. Compositionally zoned units and evolution of volcanoes through time provide a wealth of eruptive and pre-eruptive information. Additionally, because most volcano contacts are, in some sense, unconformable, much can be learned by scrutinizing the geometry, lithology, and missing time at contacts. Establishing compositional variations, the range of eruptive styles and ages of events contribute to reconstructing the complex interaction between short-lived constructional episodes of edifice growth, when fresh material is deposited at the surface, and longer periods of quiescence during which the edifice and terrain are gradually degraded and deposits remobilized. Edifice destruction, or remobilization of previously emplaced deposits, may also happen instantaneously pre-, syn-, or post-eruption, due to rapid deposition of newly emplaced units, or to caldera (vertical) or sector (lateral) collapse. These rapid shifts between construction and destruction lead to the formation, and sometimes chaotic stacking, of rock formations that are often delineated by unconformities and abundant reworked intervals (epiclastic deposits), depending on the nature of the erupted material (e.g., loose volcaniclastic debris vs. coherent lava), topography around the volcano, and local climate. **Figure 1** presents a small selection of outcrop-scale photos of a range of volcanic deposits and rocks.

When making initial field observations, use of clear, generic terminology to describe volcanic products is the best way to support later robust interpretations. Avoiding the tendency to prematurely apply genetic terminology based on a limited number of observations will encourage consideration of all observations, and not only those that fit preconceived notions. For detailed guidance on terminology and types of observations necessary to reach an interpretation of volcanic rock and deposit emplacement mechanisms, we refer to [5]. Those authors propose a multi-step iterative procedure that can be applied to any type of volcanic succession, including ancient terrains, and to both coherent rocks (lavas and intrusions) through fragmental and volcaniclastic facies. The procedure includes describing lithological and petrological characteristics, followed by describing outcrop- or drill core-scale depositional and emplacement features, which together lead to a genetic deposit name [5].

[Additional Reading QR2: "Volcano-geologic mapping and facies descriptions"]

In the following sections we provide an overview of some practical aspects of making volcano-geologic maps and compiling chrono-stratigraphic frameworks, and present two case studies. For more detailed and comprehensive overviews on the principles of stratigraphy and mapping, we refer the volcanological community to recent compilations [1-6].

Figure 1: *Outcrop-scale photos of a range of volcanic rocks and deposits* ***(a)*** *Las Juntas andesite lava flow, Tungurahua, Ecuador, showing cooling fractures at variable scales, including columnar jointing at the base;* ***(b)*** *Photo of lava flows in the Southwest Rift Zone of Kīlauea, Hawaiʻi, USA, demonstrating the principle of superposition, and differences in weathering and vegetation based on their relative ages. The dark black lava flow erupted in 1823 CE; it overlies the reddish-brown lava flow (bottom right), and both flows overlie an older lava flow (back right) that is well vegetated with grass;* ***(c)*** *Valley-filling and sintered ignimbrite deposits, Valley of 10,000 Smokes, Alaska, USA;* ***(d)*** *Angular unconformity in a sequence of*

pyroclastic fallout deposits at Totorillas, Chimborazo, Ecuador; ***(e)*** *Coherent andesitic lava flows (aeg) overlaying andesitic pyroclastic facies (ahc), adjacent to intrusive complex of Hodge Crest at Prouty headwall, South Sister, Oregon, USA;* ***(f)*** *Rhyolite lava flow of Devils Chain (rdc), South Sister, Oregon, USA. For unit abbreviations of photos* ***(e-f)*** *and sequence interpretations, see Case Study 1. All photos by the authors.*

Planning and preparing for fieldwork

The level of detail and amount of time required when mapping and establishing stratigraphy will depend on the objectives and desired end-products of the study. For example, a geologic map of an entire volcanic complex documenting its complete 100s-kyr-time-volume-compositional record can take a decade (**Case Study 1**); and a Holocene stratigraphic profile that compiles frequency-magnitude relationships of past eruptions to support a hazard assessment can take several years to complete (**Case Study 2**). However, an isopach map of a single widespread pyroclastic deposit, or a detailed profile of strata within deposits that document changing behavior during a single eruption may take less time. Regardless of the scale and scope of fieldwork that underlies the mapping, appropriate field kit and preparation are important in being able to achieve the mapping and scientific objectives safely and thoroughly, while considering ethics of fieldwork, especially for work in sensitive areas, and engaging in appropriate collaborations (**Fig 2 / How-To Box 1**).

[Additional Reading QR3: "Collaborations"]

Field kit and preparation

Essential kit
- Notebook(s), pens, pencils
- Base map (printed or digital)
- GPS
- Hammer
- Geological compass
- Trowel, spade
- Spatula, gardening tool (scraper), brushes
- Tape measure, calliper
- Hand lens
- Camera
- Sample bags, marker pens
- Spare batteries, battery charger for anything digital
- ...

Health and Safety ***(depending on fieldwork location)***
- Canteen/water bottles
- Appropriate footwear, clothes and accessories for a variety of meteorological conditions (sunscreen, sunglasses, hat, rain gear, etc.)
- Insect repellent, bear spray, antihistamines
- Overnight gear (if necessary): tent, sleeping bag, etc.
- Flashlight/headlamp
- Hard hat, sturdy gloves, goggles/safety glasses
- First-aid kit, emergency numbers and contact details, water purification system, medication
- For remote field work: communication device appropriate for location (e.g., satellite phone, InReach, emergency beacon, radio)
- Communication and emergency locator beacon
- Oxygen, acid gas, N95 masks (depending on environment)
- Walking sticks
- EpiPen, any other life-saving medication
- ...

Advanced kit ***(depending on objectives)***
- Tablet/smartphone with installed mapping or stratigraphy apps (e.g., GeoMapApp, StraboSpot, QField for QGIS)
- Water spray flask to reveal sedimentary structures
- Lacquer peels for high-resolution outcrop observation and sampling
- Tarpaulin sheet, field balance, sieves, calipers, etc.
- Drone
- Laser Rangefinder
- Binoculars
- Portable XRF
- ...

Essential preparation
- Literature review
- Base maps from remote sensing or previous mapping studies
- Identify target locations/areas, e.g. using topographic maps, Google Earth or existing literature
- Liaise with (local) colleagues and communicate objectives and planning
- Obtain appropriate permits (visa, research permit, national park entry, etc.). Note that some of these may require planning well in advance.
- Prepare risk assessment to include both natural (fauna, flora, geohazards) and human-induced risks
- ...

Figure 2 (How-To Box 1): *Summary overview of things to consider before going the field, including kit to take and precautionary preparations*

From fieldwork to compiling a map

A first-order task when mapping is identifying major constructive and destructive geomorphic features (e.g. (strato)cones, lava flows, tuff rings, maars, landslide scars) and establishing their distributions. Geomorphic features, drainage patterns, regional faults, and structural lineaments are all considered in understanding the topography of the landscape. Remote sensing data (satellite imagery, lidar datasets, and aerial photography) and digital elevation models derived from the imagery are useful, and topographic and road maps essential. Careful consideration of all the imagery and maps permits some degree of evaluating accessibility of areas and outcrops prior to fieldwork and is invaluable once "on the ground."

Most geologic mapping of volcanoes and stratigraphic correlations are initially based on a lithostratigraphic approach, meaning that rocks are distinguished, characterized and preliminarily assigned to units based on lithological properties, stratigraphic positions and distributions. It is important to clearly describe every relevant feature at the scale of the outcrop and deposit, and of individual samples or clasts, and to separate these descriptions as much as possible from genetic interpretations. Such complete descriptions provide a solid basis for a unit's final definition, its spatio-temporal position, and interpretive conclusions. Units can be assigned as finely as they can be distinguished. Some lavas can be mapped as individual flows, others as packages of flows derived from the same vent and eruptive episode. Fragmental and sedimentary deposits of similar lithological properties are referred to as facies, but a single facies may repeat across time and stratigraphy and occur independently in unrelated spatial contexts across a map. A formal lithostratigraphic unit is discrete and has clearly defined upper and lower boundaries within a stratigraphic succession but may contain internal facies variations. Such variations can be especially important in volcanic sequences, where characteristics of units can change with distance from vent [1-4].

Lithostratigraphic units can be placed in a chronological context first by establishing field-based stratigraphic relations, then by augmenting those with geochronology (see below). The former involves correlation of outcrop remnants and evaluation of how different units are juxtaposed. Position and distribution of the units relative to the landscape is also an important consideration. For instance, it is common for older lava flows to remain as ridge-capping remnants high above younger lavas that fill an adjacent glacial or river-carved valley below [6]. Upper and lower limits of identified units may take the form of paleosols, erosive surfaces, or unconformities, which represent breaks in time or quiescence between eruptions. In some cases, unit boundaries are subtle and only revealed through detailed analyses of chemical or mineralogical composition or geochronology [2]. In the last few decades, mapping of pyroclastic volcanic sequences has sometimes included the concept of unconformity bounded stratigraphic units (UBSUs), which allows identification of an unconformity hierarchy, and hence, of the enclosed volcanic successions [3]. For example, a short pause or simple change in style during an eruption will produce depositional breaks that can be traced only within the deposits of that specific eruption. On the other hand, catastrophic destructive phenomena such as landslides and caldera collapse can quickly cause large-scale unconformities. Such unconformities therefore do not really represent a significant hiatus in time and there is no consensus whether they should be considered to bound stratigraphic units [1-2]. Given the strong lateral and vertical facies variations that are characteristic of many fragmental volcanic deposits, including those representing a single eruption, it remains important to start from a lithologic and facies-based approach in compiling maps and stratigraphic profiles, especially in volcanic terrains that have not yet been mapped in detail. Identifying and mapping successive products of each vent on a volcano or in a volcanic field provides a first-order clustering of map units useful in documenting eruptive history. Lavas, PDCs, pyroclastic falls, epiclastic deposits etc., might all be products of the same eruptive episode. Formal assignment of stratigraphic hierarchy into groups, formations and members can only happen when one is adequately confident that all units have been distinguished and defined, and this happens only late in the iterative process of compiling a geologic map and/or chronostratigraphic framework supported by adequate compositional and geochronological data.

Key descriptive features

Some key features to consider when describing volcanic rocks and deposits at outcrops include how surrounding topography has influenced distribution of lavas and fragmental deposits. Other considerations include rock texture, morphology, crystallinity or phenocryst content (if coherent), deposit granulometry, sorting and componentry (if volcaniclastic), vesicularity, mineralogy, depositional structures, thicknesses, and any other defining characteristics. Some of these, and a selection of appropriate sampling strategies, are listed in **Figure 3 / How-To Box 2**. Following a systematic procedure with a clear separation of description and interpretation will help to assign correct genetic names to any volcanic package, including most of those where the original lithofacies might be heavily modified, deformed, or completely overprinted by alteration [5].

Describing and sampling volcanic deposits in the field

Descriptions

Large scale
- Geomorphology of the surrounding terrain
- Size, orientation and nature of the outcrop
- Structural features
- ...

Deposit / outcrop-scale
- Nature of contacts, soil development, ...
- Deposit/unit thickness and possible lateral variations
- Lava flow morphology and textures, presence of cooling fractures, ...
- Sedimentary structures (layering, cross-bedding, ...)
- Degree of lithification (welding, cementation, ...)
- Grain size : mode, minimum, maximum grain size
- Sorting and grading, any vertical or horizontal variations
- Clast componentry (juveniles, crystals, accessory clasts, ...)
- ...

Sample / clast-scale
- Colour
- Morphology
- Texture
- Vesicularity
- Mineralogy
- ...

Sampling strategies

For mineralogy and (bulk) geochemistry
- Coherent facies: fist-size sample, from the core or top of the unit/flow, without visible weathering or secondary minerals. Some features like vesicularity and mineralogy may vary widely across the flow, and from proximal to distal locations.
- Pyroclastic facies: vertical channel samples across the entire thickness of a deposit or subsection. Individual clasts can be collected with a stratigraphic context. Avoid clast breakage by loosely scraping the outcrop surface if possible. Sample top units first to avoid cross-contamination.

For geochronology
- ^{14}C dating: individual pieces of charcoal or other organic material. Bulk soils to be avoided if possible. Large trunks of trees sampled on the outside represent their youngest age when incorporated in a deposit.
- Ar-Ar dating: groundmass or crystals. The amount necessary will depend on rock type, texture, and crystallinity, and can range from a few tens of grams to a kilogram of material. Avoid glassy, vesicular rocks.
- Cosmogenic dating: groundmass or crystals (depending on the isotope system used), and usually requires several hundred grams in an open setting (not being shielded by high topography).
- Paleomagnetic drilling of rocks can be used for correlations and in the right context provide age constraints. Contingent upon skill with a drill and ability to orient and extract cores to be measured in a magnetometer.

For componentry / grain size analysis
- Grain size and componentry analyses on coarse fractions (>4 mm) of pyroclastics can be performed in the field. Take finer fractions to the laboratory for further analysis.

Figure 3 (How-To Box 2): *Non-exhaustive overview of features to describe when mapping volcanic rocks and deposits at a range of scales in the field, and some practical aspects to consider when sampling for* *different purposes. Several features described in the field, such as sorting, modal abundance of components, or roundness of clasts, are ideally estimated using visual comparison charts.*

A brief overview of key volcanic rocks and deposits, with reference to relevant chapters in this volume, is provided in **Table 1**. For detailed overviews of eruption processes, emplacement mechanisms, and resulting deposit features, we refer to these relevant chapters, and [1].

Table 1. *Overview of key categories of volcanic rocks and deposits. For an exhaustive overview of classes of coherent and volcaniclastic rocks and their essential characteristics, we refer to relevant chapters in this volume and [1].*

Deposit observed (described)	**Depositional mechanism (interpreted)**	**Chapter**
Coherent lava	Lava flow/dome	Part 3, Chapter 3.1-3.2
Well-sorted pyroclastic deposit	Pyroclastic air fall (aggradation)	Part 3, Chapter 4.3
Plastic flattened clast, or impact-/sag-structure under clast	Ballistic transport of bomb or block	Part 3, Chapter 4.3
Poorly sorted pyroclastic deposit	Dilute pyroclastic density currents (stepwise aggradation / fluid-escape / traction-dominated flow boundary zone)	Part 3, Chapter 4.4
	High-concentration pyroclastic density currents (stepwise aggradation/ granular-flow/ fluid-escape dominated flow boundary zone)	Part 3, Chapter 4.3
Poorly sorted volcaniclastic sediment	Low-concentration lahars	Part 3, Chapter 5.1
	High-concentration lahars	Part 3, Chapter 5.1
	Debris-Avalanche	Part 3, Chapter 5.4
	Moraine	Part 3, Chapter 2.3
Well-sorted volcaniclastic sediment	Aeolian remobilized ash	Part 3, Chapter 5.2
Poorly or well-sorted breccia with altered matrix	Hyaloclastite	Part 3, Chapter 2.2-2.3

Map units characterized in the field using a hand lens are further evaluated petrographically and compositionally in the laboratory, and this laboratory work may be synchronous with field mapping over several seasons in an iterative process (**Case Study 1**). From macroscopic to microscopic scales, observations of vesicularity (vesicle abundance and shape, vesicle size distribution), crystallinity (crystal abundance, shape and organization, crystal size distribution, mineral paragenesis), and groundmass (presence of microlites, glass, devitrification), along with degree and type of alteration can provide relevant information about volcanic rocks of interest. Defining eruptive units and timeframes, however, requires ample additional compositional and geochronological data. The Sm-Nd, K-Ar, ^{40}Ar-^{39}Ar, and U-Th-Pb isotopic systems are generally applied to date Pleistocene-age and older volcanic rocks, whereas U-series, ^{14}C, ^{40}Ar-^{39}Ar, and cosmogenic dating methods, such as ^{3}He and ^{36}Cl, are suitable for Pleistocene and Holocene age volcanic rocks [7].

[Additional Reading QR4: "Chronology methods"]

Temporal (e.g., chrono-stratigraphic) history is often put into context with magma compositions, source vents/volcanoes, deposit distributions and volumes, and eruptive styles and magnitudes. Temporal information that is crucial to understanding eruptive histories and long-term volcano evolution includes eruption recurrence intervals, and whether eruptions tend to occur as clustered events, statistically individual events, or a mix over a volcano's lifetime. Conventionally, ages are integrated with location of source vent to determine lava and pyroclastic density current extents and airfall tephra dispersal patterns. This helps in constraining areas that have been inundated by products from effusive and explosive eruptions across local to regional scales through time, and yield insights into edifice growth versus collapse and erosion. Integrating the spatio-temporal framework with composition and mineral data, such as mafic versus silicic magma contributions, is also useful for clarifying volcano source provenance, and interpreting magma plumbing systems that can experience changes in magma genesis, flux, storage zone development, and transport [8]. Understanding the plumbing system provides a proxy by which to better interpret seismic and other geophysical data at active volcanoes [9] or at volcanoes prospected for geothermal exploitation.

[Additional Reading QR5: "Magma plumbing systems, petrological monitoring"]

Case Study 1: Geologic map of South Sister, Oregon, USA

The Three Sisters complex is a cluster of glaciated stratovolcanoes (North, Middle, and South Sister) in the Cascade Range of Oregon, USA. Glacial erosion has significantly shaped the morphology of this complex; however, the volcanoes have been sufficiently active in the Quaternary for most landforms to be the result of constructional processes. Uplift centered about 5 km west of South Sister was detected by satellite and GPS between the mid-1990s and mid-2000s and was interpreted to be caused by a magmatic intrusion. Hildreth et al. [10] present a detailed geologic map at 1:24,000 scale, covering an area of exclusively Quaternary volcanic rocks and derived epiclastic deposits. The map was constructed during about 200 days of fieldwork, mostly on foot, spanning a period of almost 10 years. In total, 145 volcanic units were mapped, with each analyzed for petrography and geochemistry in an iterative process that gradually resulted in the published map. Part of those petrological and geochemical investigations were completed as part of topical studies. The chronostratigraphic framework is constrained by ^{40}Ar-^{39}Ar dating on most pre-Holocene rocks in combination with field-established stratigraphic relations to piece together the complete volcano history [10].

[Additional Reading QR6: "Three Sisters, Oregon, USA"]

North Sister is a glacially dissected basaltic andesite edifice that is part of the mafic periphery of the complex and had its main constructive period between ~120 – 45 ka. During this period, several major unconformities are identified, indicating multistage edifice growth. Middle Sister, an andesite-basalt-dacite cone, was built during the interval from 48 to 14 ka but mostly between 25 and 18 ka, overlapping in time with South Sister. Activity at South Sister began with eruption of predominantly rhyolitic lava flows and domes between ~50 – 30 ka. Toward the end of this period, rhyodacitic lavas also appear, followed by construction of the main andesitic edifice [11]. This relative sequence is visible in **Figure 4**, with older rhyolite units at the southern and northern base of the edifice (reds), followed by dacites (purples) and andesites erupted from the summit (oranges). The youngest activity, however, is rhyolitic, with the emplacement at ~2.2 ka of lava flows and tephra deposits (unit rrm) and at ~2 ka of dike-fed lavas along a N-S trending chain of eruptive vents (unit rdc; **Figure 4**; [10, 11]).

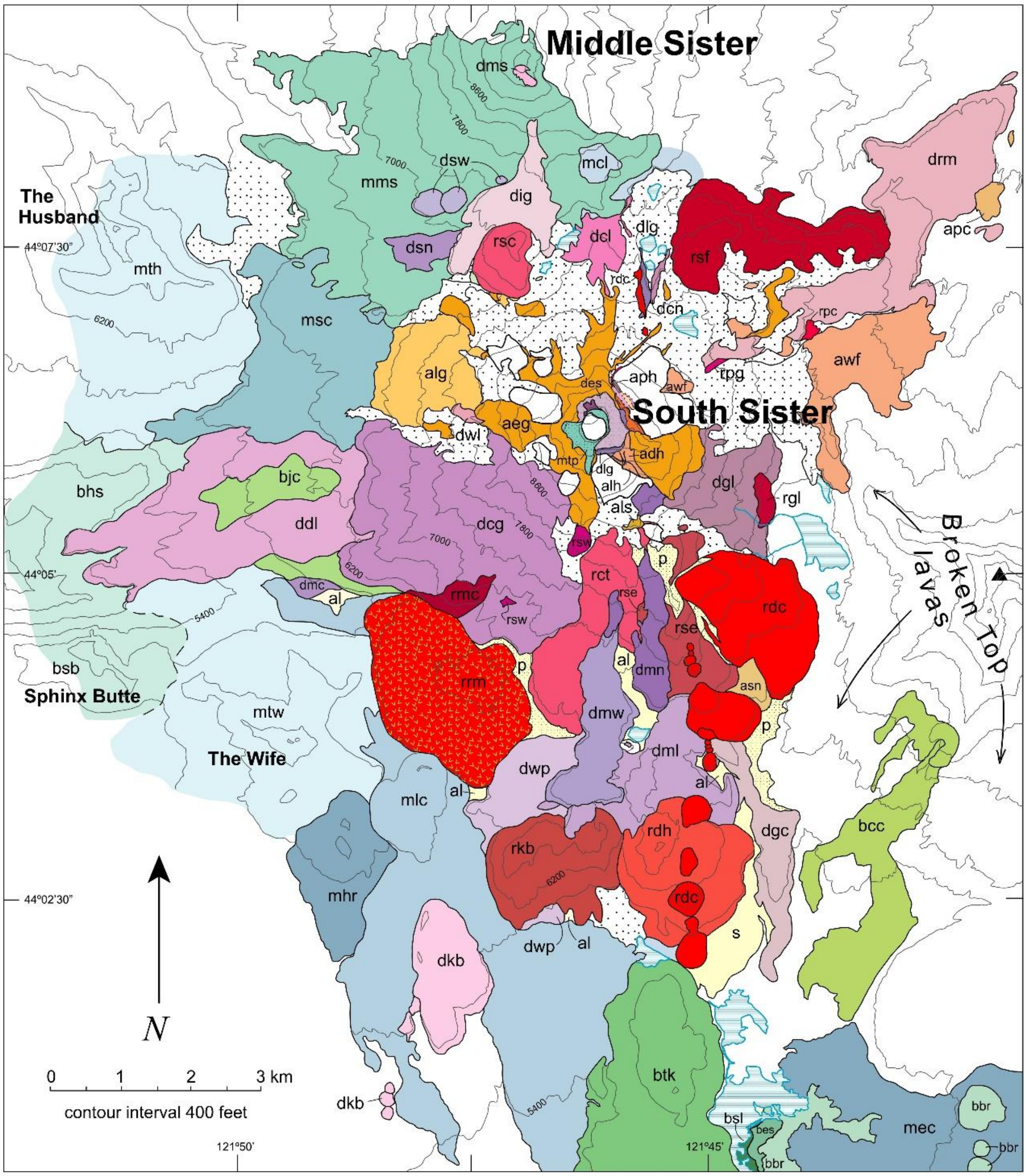

Figure 4 (Case Study 1) *Simplified geologic map of South Sister and its periphery, and several Middle Sister units, all of which are part of the complete Three Sisters complex in Oregon, USA. North Sister is located ~7 km north of South Sister. Colored geologic units are labeled with 3-letter unit designations; the first letter of each label indicates composition: b=basalt; m=basaltic andesite (mafic units are shades of green and blue); d=dacite (pinks and purples); a=andesite (oranges); r=rhyodacite and rhyolite (reds). Figure from [11]. For a full version of the Three Sisters volcanic cluster map, including a legend and pamphlet with detailed unit descriptions and compositional and geochronological data, see [10].*

Tephrostratigraphy and tephrochronology

Tephrostratigraphy is the stratigraphic reconstruction of a sequence of pyroclastic deposits (fallout and PDC) that are usually more spatially widespread than products of effusive eruptions. Documenting tephra distribution provides opportunities to estimate deposit volumes and eruption style, and thus corresponding magnitudes of these eruptions [E18]. Whereas a volcano geologic map represents the long-term evolution of a volcanic system or complex, hazard-informing tephrostratigraphic frameworks are most often limited to the latest Quaternary, due to limited preservation potential of non-consolidated pyroclastic deposits in humid climates or previously glaciated regions. When absolute geochronological information can be integrated with a tephrostratigraphic framework (i.e. tephrochronology), tephrostratigraphy becomes an effective tool to constrain eruption recurrence intervals, as well as long-term eruptive rates (10^2–10^6 years) at the scale of an individual volcano or complex, or of a volcanic region. Because tephra deposits, particularly from widespread tephra fallout, are emplaced near-instantaneously (generally, hours to months) in different sedimentary environments (terrestrial, lacustrine, marine, glacial), they have the potential to form an isochron or 'time-horizon' marker bed in the stratigraphic record. A well-defined absolute age of a well-characterized ("fingerprinted") tephra deposit may then be transferred across sedimentary profiles, which may be studied in different disciplines beyond volcanology, including paleoecology, palaeoclimatology, archaeology, etc. [12]. For mapping purposes, tephrostratigraphic records are most useful when the deposits can be correlated to the vent(s) from which they initiated.

To support correlations between sedimentary profiles and environments, and potentially transfer ages across them, thorough documentation of physical and chemical characteristics of a tephra deposit is required [13]. Modern mobile applications can be useful in systematically recording all the useful information and measurements and directly import them into a centralized and geo-referenced database. Ideally, properties that are used to uniquely fingerprint and correlate tephra deposits are independent of distance from eruptive source or deposit preservation conditions. Lithological descriptions in the field or laboratory (e.g., on sediment cores) include basic characterizations such as thickness, color, grain size distribution, depositional fabric, and componentry (e.g., proportion of juvenile and accidental lithic clasts, mineral assemblage). Some of these features can, however, change with distance from source, and for this reason, geochemical fingerprinting is often essential to fully characterize tephra deposits and support correlations.

Geochemical fingerprinting is usually performed on juvenile components (e.g. volcanic glass shards and phenocrysts). Unlike the bulk composition of a pyroclastic deposit, glass and/or mineral compositions in deposits from a particular eruption are more likely to be distinct from those of other eruptions (from the same or other volcanoes) due to processes of magmatic evolution. Both silicate and Fe-Ti oxide minerals have been successfully used to fingerprint and correlate tephra deposits (**Case Study 2**). However, because distal to ultra-distal tephra deposits (100s–1000s km from source) are generally dominated by volcanic glass shards, and because the glass fraction tends to also dominate proximal sequences, geochemical fingerprinting of glassy groundmass remains the most common tool to support tephrochronological correlations [12, 14]. Improvements in micro-sampling and analytical techniques on a limited number of individual, small glass shards have allowed significant progress in studies of ultra-distal tephra deposits that may be detected as cryptotephras in glacial, lacustrine, or other sedimentary systems [14, 15].

Accurately identifying sources and correlating (crypto)tephra layers relies on the availability of a database of chemical compositions of widespread, regional correlative deposits. Such databases may be used to identify chemically similar, correlative tephras using statistical tools such as Principal Component Analysis or k-means clustering. Even with geochemical fingerprinting techniques, however, distinguishing between different eruptions may still be difficult, as chemical compositions of products from a single volcano tend to be overlapping. Thus, additional constraints from field observations, physical characterizations of tephra, and other data such as componentry, may help support correlations.

[Additional Reading QR7: "Tephrostratigraphy and Tephrochronology: methods, databases and case studies"]

Construction of a solid chrono-stratigraphic framework, and volcano-geologic map, is founded on rigorous field observations and the ability to investigate adequate outcrops and samples. In some cases, finding suitable material for dating poses a challenge. For example, radiometric dating systems generally use specific minerals, appropriate groundmass, or charcoal that are not always present in volcanic deposits of interest. As a result, it may be challenging to obtain absolute chronologies for major evolutionary stages of a volcanic system or for each individual lithostratigraphic unit or eruption. Even when suitable material is available for radiometric dating, if a sequence contains an overabundance of deposits emplaced at rates faster than the accuracy of the dating technique, it is not feasible to date every single unit. As a result, eruption history databases [16] do not always contain all the relevant information that could be retrieved from a (Holocene) stratigraphic framework, and care should be taken when using them as a basis for probabilistic hazard assessment [E3].

Case study 2: The post-glacial tephrostratigraphic framework of Mocho-Choshuenco volcano, Chile.

Mocho-Choshuenco, a volcanic complex in the Southern Volcanic Zone of the Andes in southern Chile, was severely glaciated during the Last Glacial Maximum at ~25-16 ka. On-land tephrostratigraphic records comprise unconsolidated volcanic deposits and soils that are easily eroded, and are thus typically limited to the post-glacial period. Only marine or rare lacustrine exposures reveal longer-term records of repeated volcanic ash deposition during glacial periods. Rawson et al. [17] present a high-resolution tephrostratigraphic reconstruction of Mocho-Choshuenco's post-glacial history based on detailed field observations from ~400 locations, including distal tephra sections up to 70 km from the central edifice. Outcrop exposure and deposit preservation are limited due to dense vegetation and high annual rainfall, so smaller-scale deposits are likely missing from the record. Field observations were combined with geochemical (glass and Fe-Ti oxide major and minor element composition) and geochronological (radiocarbon) data and checked against each other in an iterative process to compile the composite stratigraphy. A Bayesian statistical approach on this composite profile, into which several units have multiple radiocarbon dates associated with them, allowed compiling an age model and assigning age probability functions to each individual unit in the profile. The most widespread deposits were identified in at least 10 different locations, and isopach (equal thickness) and isopleth (equal maximum grain size) maps allowed estimates of eruption magnitudes [E18].

The post-glacial tephrostratigraphic record at Mocho-Choshuenco includes 25 well-defined and chemically fingerprinted lithostratigraphic units (**Figure 5**) some with sub-units defined by facies variations, and numerous poorly preserved interbedded scoria fallout deposits. A total of ~75 discrete post-glacial eruptions are identified, spanning a history of ~16.5 kyr of explosive activity, and corresponding to an average eruption frequency of ~220 years. About half of the eruptions originated from (monogenetic) scoria cones along the flanks of the complex, and four were Plinian eruptions of magnitudes between 5.0 and 5.7 (**Figure 5)**, that produced widespread tephra fallout and/or PDC deposits of andesitic to rhyodacitic compositions. Since the last major eruption (~ 1.7-1.5 ka) the ten youngest units are predominantly scoria fallout deposits of andesitic compositions, including the most recent historical eruption in 1864 CE [17].

[Additional Reading QR8: "Southern and Austral Volcanic Zone, Chile"]

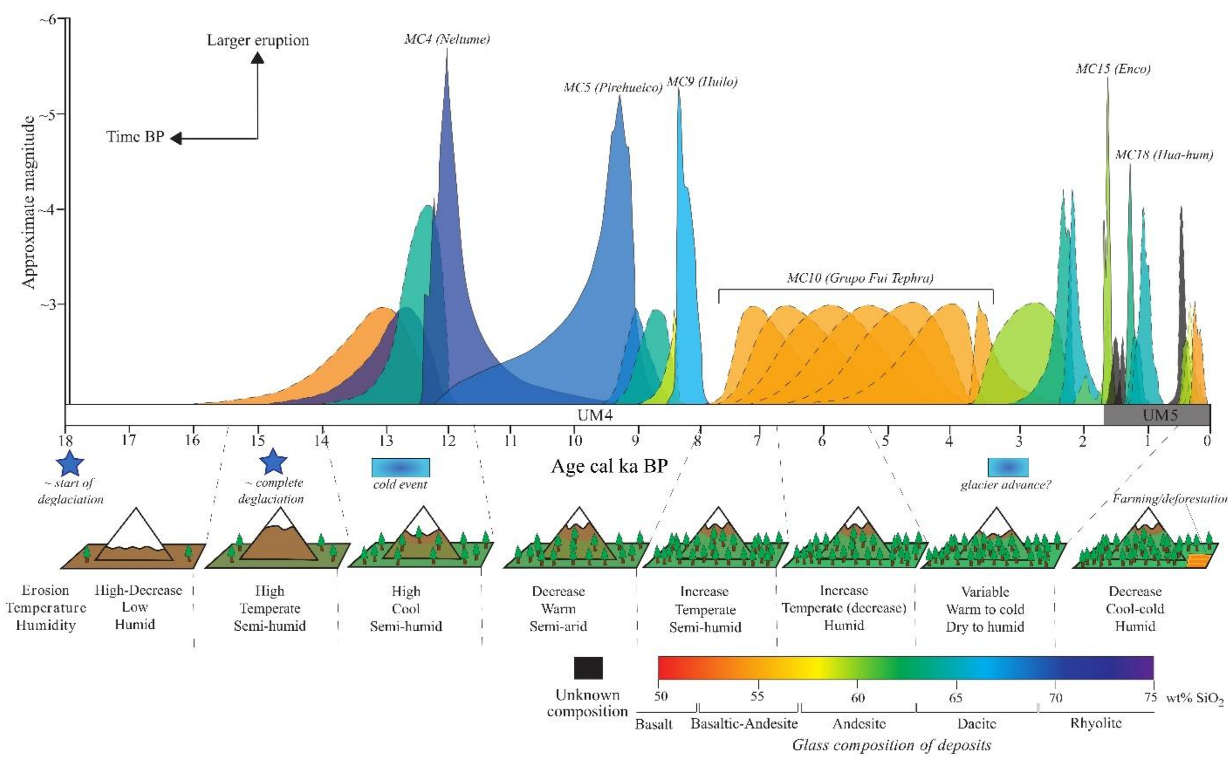

Figure 5 *Summary of explosive eruptions from Mocho-Choshuenco since the onset of deglaciation at ~18 ka. Each of the 25 chemically and stratigraphically constrained units are represented by their modeled age probability function, with the peak height scaled to the estimated eruption magnitude and color-coded by chemical composition. Note that major Plinian eruptions are not evenly spaced in time, which is attributed to a response of the magmatic plumbing systems to deglaciation. Erosion rates, temperature, humidity and vegetation density inferred from paleoenvironmental reconstructions from a lake sediment core ~90 km South of Mocho-Choshuenco (for references, see Additional Reading). Figure modified from [17].*

Preservation bias: insights from modern eruptions

Recent eruptions and careful tracing of their deposits in near-real-time help in evaluating preservation potential and bias in the geological record. Three examples follow: (1) The small-to-moderate 2011-12 subplinian eruption of Cordón Caulle, Chile, dispersed volcanic ash over Patagonia in a lobate dispersal pattern and with multiple vertical grain-size variations in the deposits due to the long-lasting and pulsating nature of the eruption. The present-day deposit is poorly or not preserved except in localized, near-vent areas due to post-depositional erosion and remobilization, including by wind. This suggests that eruptions of pyroclastic material smaller than VEI or Magnitude 3 are unlikely to be preserved in the geological record, except in lake sediment and peat cores. Even in lake sediment cores, interpretations of volcanic ash-layer grain size and thickness should be treated with caution. Tephra from the 2011-12 Cordón Caulle eruption was dispersed entirely eastward of the volcano, yet a volcanic ash layer was found in sediments of Lake Puyehue located to its west due to in-washing from the lake's catchment [18]. Therefore, this ash was not formed as a primary pyroclastic deposit but was epiclastic in origin. Complicating distribution analysis still further, the grain size and thickness of this ash increased with distance from source, likely because of intra-lake currents distributing the sediment into different sub-basins of the lake [18].

[Additional Reading QR9: "Modern eruptions"]

(2) In Iceland, three distinct lava flows erupted from a fissure at Fagradallsfjall during three different eruptions between 2021 and 2023. The flows overlap with each other and are likely to leave a mostly coherent lava flow in the geological record of interbedded massive and auto-brecciated facies. From an operational monitoring perspective, they are considered different eruptions because the pause in activity between them was more than three months [16]. However, on a geologic map or in a stratigraphic profile, the products of these lava flows would likely be grouped into one lithostratigraphic unit and interpreted as the products of one eruption.

(3) The 2022 paroxysmal submarine eruption of Hunga Tonga-Hunga Haʻapai demonstrated the generally poor knowledge of submerged or partially submerged volcanoes and their underestimated hazards. Mapping such volcanoes represents a major challenge, as underwater geological surveying is almost entirely based on high-resolution bathymetric reconstructions, limited visual inspections, and sampling by remotely operated vehicles [19].

Recent advances

Since the end of the late 2000s, Uncrewed Aerial Vehicles (UAVs), commonly referred to as drones, have revolutionized fieldwork, especially for volcanic mapping [20]. UAVs enhance safety and improve accessibility to rugged, often unstable and steep volcanic terrains. The evolution of propulsion systems, battery technology, as well as the miniaturization of sensors and the improvement of data transmission capabilities have collectively propelled drones to operate at distances several kilometers from active vents and hazardous areas.

The use of a variety of sensors, including visible RGB, thermal, multispectral, and lidar, enables UAVs to capture high-resolution imagery, down to centimeter scale, along with precise positioning using Real Time

Kinematics (RTK). This facilitates the creation of georeferenced rasters such as orthomosaics and digital elevation models using Structure from Motion (SfM) photogrammetry techniques (**Figure 6**). Moreover, drones can reconstruct structures and landscape in 3D with unprecedented accuracy, which is helpful in better understanding volcanic successions and underlying processes.

One of the major advances associated with UAVs is the ability to collect data during volcanic events that can be processed in near-real-time, enabling volcanologists to quickly assess volcanic hazards and update existing maps. Drones are now extensively used to produce maps of lava fields and estimate dome growth. This is also possible because UAVs are often more cost-effective than traditional aerial surveys, which is extremely helpful for volcanic observatories working on a limited budget.

[Additional Reading QR10: "Recent advances"]

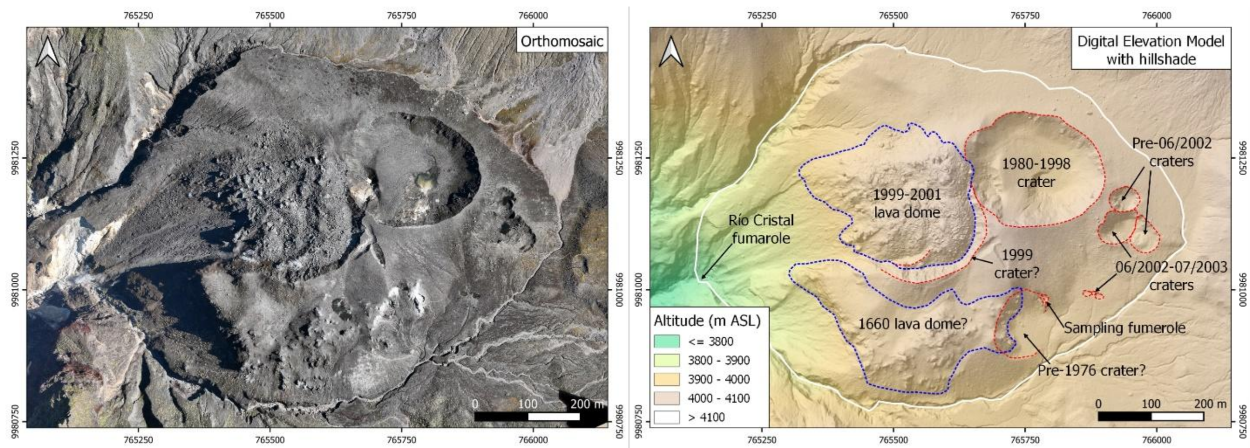

Figure 6 *Orthomosaic (left, GSD 11.4 cm/px) and Digital Elevation Model with hillshade (right, GSD 23.4 cm/px) of Cristal dome complex at Guagua Pichincha volcano, Ecuador. The red dashed lines correspond to the crater rims and the blue dashed lines to the lava domes. The coordinate system is WGS 84, UTM zone 17S.*

Summary

Geologic maps and stratigraphic reconstructions of volcanoes provide fundamental information for studies on volcanic hazards and probabilistic hazard assessments that may be used by volcano observatories and other agencies to inform the public and other stakeholders. Such work also supports other volcanological studies that require an understanding of the evolution of volcano-magmatic systems; it can support surface exploration studies for geothermal development; and it can be used in ancient volcanic terrains for identifying mineral resources. Mapping and stratigraphy rely on rigorous fieldwork that ultimately constructs time-volume-composition records that characterize magnitudes, styles, and periodicity of all past activity. Recognizing the full range of past behavior of an edifice or volcanic field provides an essential complement to real-time instrumental monitoring.

When mapping a particular volcanic area, every piece of evidence, from macroscopic to microscopic scale, becomes relevant to achieve a rigorous and precise interpretation. Modern technologies simplify field preparations, including the selection of targeted areas and interpretations of large-scale structures and geomorphological features. Field observations are important in distinguishing contact relations and unconformities of variable scales, which are critical to understanding the stratigraphic sequence, and which must be confirmed with geochronological data. Detailed geomorphological and structural studies must be done to detect possible regional controls on volcanic morphology and activity. An exhaustive lithofacies analysis should be complemented with geochemical data to support stratigraphic correlations. Meaningful definition of eruptive units and temporally clustered eruptive groups requires ample compositional and geochronological data. Laboratory work is synchronous with field mapping and typically iterative over several seasons.

Construction of tephrostratigraphic frameworks is reliant on geochemical fingerprinting to verify correlations. This fingerprinting may include a combination of glass or mineral major- and trace-element chemistry, and componentry analysis. Advances in sample preparation methods and analytical techniques now allow correlating volcanic ash layers as much as 1000s of kilometers from source. Statistical analyses and machine learning techniques can help refine correlations of large datasets, but should still be verified by field constraints, especially in cases where there are similar chemical compositions in a stratigraphic sequence. Importantly, study of tephras aims not only at mapping timelines but at linking them to vent sites on the edifice, correlating the chronology of cone lavas to that of fragmental deposits. Mapping and stratigraphic studies together can develop an integrated stratigraphic, chronological, structural, geomorphic, and petrologic framework that, combined, document comprehensive eruptive histories.

Disclaimer

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Figures & Tables

Figure 1: Outcrop-scale photos of a range of volcanic rocks and deposits **(a)** Las Juntas andesite lava flow, Tungurahua, Ecuador, showing cooling fractures at variable scales, including columnar jointing at the base; **(b)** Photo of lava flows in the Southwest Rift Zone of Kīlauea, Hawaiʻi, USA, demonstrating the principle of superposition, and differences in weathering and vegetation based on their relative ages. The dark black lava flow erupted in 1823 CE; it overlies the reddish-brown lava flow (bottom right), and both flows overlie an older lava flow (back right) that is well vegetated with grass; **(c)** Valley-filling and sintered ignimbrite deposits, Valley of 10,000 Smokes, Alaska, USA; **(d)** Angular unconformity in a sequence of pyroclastic fallout deposits at Totorillas, Chimborazo, Ecuador; **(e)** Coherent andesitic lava flows (aeg) overlaying andesitic pyroclastic facies (ahc), adjacent to intrusive complex of Hodge Crest at Prouty headwall, South Sister, Oregon, USA; **(f)** Rhyolite lava flow of Devils Chain (rdc), South Sister, Oregon, USA. For unit abbreviations of photos **(e-f)** and sequence interpretations, see Case Study 1. All photos by the authors.

Figure 2 (How-To Box 1): Summary overview of things to consider before going the field, including kit to take and precautionary preparations

Figure 3 (How-To Box 2): Non-exhaustive overview of features to describe when mapping volcanic rocks and deposits at a range of scales in the field, and some practical aspects to consider when sampling for different purposes. Several features described in the field, such as sorting, modal abundance of components, or roundness of clasts, are ideally estimated using visual comparison charts.

Figure 4 (Case Study 1) Simplified geologic map of South Sister, and its periphery, and several Middle Sister units, all of which are part of the complete Three Sisters complex in Oregon, USA. North Sister is located ~7 km north of South Sister. Colored geologic units are labeled with 3-letter unit designations; the first letter of each label indicates composition: b=basalt; m=basaltic andesite (mafic units are shades of green and blue); d=dacite (pinks and purples); a=andesite (oranges); r=rhyodacite and rhyolite (reds). For a full version of the Three Sisters volcanic cluster map, including a legend and pamphlet with detailed unit descriptions and compositional and geochronological data, see [11].

Figure 5 Summary of explosive eruptions from Mocho-Choshuenco since the onset of deglaciation at ~18 ka. Each of the 25 chemically and stratigraphically constrained units are represented by their modeled age probability function, with the peak height scaled to the estimated eruption magnitude and color-coded by chemical composition. Note that major Plinian eruptions are not evenly spaced in time, which is attributed to a response of the magmatic plumbing systems to deglaciation. *Erosion rates, temperature, humidity and vegetation density inferred from palaeoenvironmental reconstructions from a lake sediment core ca. 90 km South of Mocho-Choshuenco (for references, see Additional Reading).* Figure from [17].

Figure 6 Orthomosaic (left, GSD 11.4 cm/px) and Digital Elevation Model with hillshade (right, GSD 23.4 cm/px) of Cristal dome complex at Guagua Pichincha volcano, Ecuador. The red dashed lines correspond to the crater rims and the blue dashed lines to the lava domes. The coordinate system is WGS 84, UTM zone 17S.

Table 1. Overview of key categories of volcanic rocks and deposits. For an exhaustive overview of classes of coherent and volcaniclastic rocks and their essential characteristics, we refer to relevant chapters in this volume and [1].

Additional Reading

[QR1]: Mapping volcano-related resources

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