Paleomagnetism and rock magnetism as tools for volcanology

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Abstract

Paleomagnetic and rock magnetic methods for studying volcanoes and their products have been developed since the second half of the twentieth century. These methods have been used to find tephra in sediment cores, date volcanic eruptions and deposits, determine emplacement temperatures of volcanic deposits, and estimate flow directions of dikes, lava flows, and pyroclastic flow deposits. In the twenty-first century, these techniques have steadily improved and expanded, resulting in more probing and precise studies of volcanoes using paleomagnetism. We believe that continual improvement of existing techniques and the increased awareness and interest in paleomagnetic methods should allow more studies to enhance the understanding of volcanic processes.

Keywords Paleomagnetism · Volcano · Lava flow · Pyroclastic density current · Dating · Emplacement temperature

Introduction

Assemblages of magnetic minerals in volcanic rocks typically record Earth's magnetic field with high fidelity when they cool to ambient temperatures, making them ideal media for paleomagnetic studies (Brunhes 1906; Nakamura and Kikuchi 1912; Chevallier 1925; Cox and Doell 1960; Tauxe et al. 2018). In turn, this record of Earth's field behavior can be used to place age constraints on volcanic processes, and the composition, grain size, abundance, and orientation

of magnetic minerals can provide additional information on volcanic and magmatic processes (Ort et al. 2015b). Many tools that take advantage of the magnetic characteristics of erupted materials have been developed to answer pressing questions about volcanoes and their eruptions. In some cases, these tools are the most effective or the only way to answer such questions. Paleomagnetic techniques were first used for volcanic studies in the 1950s (Hatherton 1954, Hospers et al. 1954, Aramaki and Akimoto 1957), and paleomagnetic and rock magnetic approaches were applied in many ways in volcanology throughout the second half of the twentieth century (Table 1). Some prominent questions in volcanology to which paleomagnetic methods were applied to include the following:

- **Is there tephra/cryptotephra in a sediment core?** The presence of magnetic minerals in volcanic materials means that they can easily be detected among less-magnetic material through the study of magnetic susceptibility, allowing for the identification of volcanic events, such as eruptions, within a sediment core (Thompson et al. 1980) (Fig. 1a).
- **What are the relative ages of volcanic materials?** Paleosecular variation (PSV) reflects the continuous changes of the Earth's magnetic field direction and strength through time before observatory data. Localized or composite records of field change, called PSV reference curves, were created for a variety of locations worldwide (e.g., Thompson and Turner 1979; Turner

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Table 1 Compilation of volcanological questions that can be addressed with paleomagnetism and rock magnetism

Volcano question	Method	What it tells you	Key studies (pre-2000)	Past 20 years	Recent studies
Is there tephra in a sediment core?	Magnetic susceptibility scan of core	Whether there are layers of tephra (high magnetic susceptibility) in a sediment core	Thompson et al. 1980	McCanta et al. 2015; Akulich et al. 2016	Kletetschka et al. 2019; Rutledal et al. 2020
Are two volcanic deposits related?	Correlation/differentiation (inter-deposit paleomagnetic vector comparison)	Whether two volcanic deposits are temporally related based on (dis/similarity of paleomagnetic vectors	Hospers 1954; Gardner 1994; Hagstrum and Champion 1994	Speranza et al. 2012; Pinton et al. 2017	Williams-Jones et al. 2020; Downs et al. 2020
When did the volcano erupt?	Relative/numerical dating (comparison of paleomagnetic direction/intensity with regional reference PSV curve)	Relative/numerical age of the rock	Rutten 1960; Coombs et al. 1960	Speranza et al. 2006; Pavón-Carrasco et al. 2011	Morales et al. 2020; Yasuda et al. 2020
What temperature was that mass flow emplaced at?	Emplacement temperature estimation (intra-deposits paleomagnetic direction comparison)	Approximate/numerical emplacement temperature	Aramaki and Akimoto 1957; Hoblitt and Kellogg 1979	McClelland et al. 2004; Tanaka et al. 2004; Paterson et al. 2010	Lerner et al. 2019b
Which way was the lava or pyroclastic flow flowing?	Anisotropy of magnetic susceptibility	The likely flow direction of a lava or pyroclastic flow; flow processes in lavas and density currents	Ellwood 1978; Cagnoli and Tarling 1997; Palmer and MacDonald 1999	Cañón-Tapia 2004; Porreca et al. 2015; Agrò et al. 2015; Ort et al. 2015a	Njanko et al. 2020; Haag et al. 2021

and Lillis 1994; St-Onge et al. 2003). Comparison of paleomagnetic data recorded by volcanic materials to the known regional field variations described by these PSV curves allowed for the relative dating of these materials (Rutten 1960; Coombs et al. 1960) (Fig. 1c). In long lava sequences, the paleomagnetic direction can also be used to identify reversal boundaries, which can be compared to the geomagnetic polarity timescale (GPTS; Ogg 2020) to provide crude age estimates (Kristjansson et al. 1995).

- **Are adjacent lava flows from the same eruption?** Relative dating by comparing the paleomagnetic direction and/or intensity of potentially related lava flows has been used in many instances (e.g., Hospers 1954; Gardner 1994; Hagstrum and Champion 1994) for temporally correlating or differentiating flows (Fig. 1d). Identification of reversal boundaries can be used to correlate lava sequences on a larger scale, across hillsides and valleys, providing an exceptional aid in geological mapping of volcanic terrains. This can be done either with a fluxgate magnetometer or through classical paleomagnetic methods (e.g., Mankinen and Cox 1988; Herrero-Bervera and Coe, 1999; Kristjansson et al. 1995).
- **Are volcanic mass flow deposits associated with hot or cold events?** Comparison of clasts found within a mass flow deposit can allow for the determination of whether the mass flow was at a high or low temperature upon emplacement (i.e., pyroclastic flow vs. lahar) (Aramaki and Akimoto 1957; Hoblitt and Kellogg 1979) (Fig. 1b).
- **Which way was a prehistoric feeder dike, lava flow, or pyroclastic density current (PDC) flowing?** Anisotropy of magnetic susceptibility (AMS) data show the physical alignment of magnetic grains within a rock and can be used to determine the three-dimensional flow direction of a lava flow or dike, as well as to triangulate the vent location of a pyroclastic flow (e.g., Ellwood 1978; MacDonald and Palmer 1990; Cagnoli and Tarling 1997) (Fig. 1e).

The past 20 years in paleomagnetic study of volcanoes

In the past two decades, advances in the understanding of paleomagnetism and rock magnetism, new study topics, and improved paleomagnetic and rock magnetic instrumentation and measurement methods have all contributed to more expansive and precise paleomagnetic investigations of volcanologic topics. This has included improvements to already existing techniques, as well as the development of new ones (Table 1).

From relative to numerical dating

Whereas twentieth century paleomagnetic dating studies of volcanic deposits typically involved relative dating outcomes, more recent studies have been able to produce numerical age estimates (discrete ages or age ranges) for the studied volcanic materials. This advance can be attributed to both an increase in high-precision data defining local PSV reference curves and new algorithms for assessing paleomagnetic results. PSV dating depends on comparing the results of studied samples to a pre-existing reference curve for the general study area in order to assess the best fit for age results. This technique is most effective when using a local, rather than composite, reference curve (Merrill et al. 1996; Pérez-Rodríguez et al. 2021).

It is worth noting that numerical dating using paleomagnetism is still limited not just by the location of available PSV curves but also by the temporal range of those curves, which typically span at least 1 kyr, up to 10–20 kyr BP in local curves (e.g., Stanton et al. 2011; Lund et al. 2017; Sheng et al. 2019), and up to ~100,000 years BP in global models (Panovska et al. 2018). Global field models have been developed that allow for extrapolation to low-data-density regions that lack reference curves, but these are accompanied by greater uncertainty (e.g., Korte and Constable 2005; Korte et al. 2011; Pavón-Carrasco et al. 2014; Constable et al. 2016). The increasing number of high-resolution regional reference curves and better-constrained global models that have emerged in the past decades, as well as increased study of global paleointensity records, has opened a wide geographic range of volcanoes for numerical PSV dating (e.g., Panovska et al. 2018; Di Chiara 2020; Béguin et al. 2021; Mochizuki et al. 2021). The development of PSV dating tools (Pavón-Carrasco et al. 2011; Hnatyshin and Kravchinsky 2014) that use Bayesian statistics to compare the results of volcanic samples to the reference curve has allowed recent studies to obtain one or multiple discrete age ranges for a specific result, allowing for more precise dating of historic and prehistoric eruptions (Roperch et al. 2015; Yasuda et al. 2020).

Although most PSV dating studies still rely primarily on directional data, a more thorough catalog of paleointensity data has also resulted in better inputs for dating studies and extends analysis to non-oriented samples. This has resulted in an increase in the availability of paleointensity records to supplement directional data in dating studies (e.g., Carlot et al. 2004; Bowles et al. 2006; Yu 2012; Morales et al. 2020).

With the rise in numerical dating, correlation and differentiation of volcanic units can also move toward temporally correlating lava flows using statistically obtained age estimates (Speranza et al. 2012; Pinton et al. 2017). PSV dating

b) Were the deposits hot and how hot?

a) Is there tephra in a sediment core?

c) How old is the volcanic unit?

e) What direction did the lava or ignimbrite flow?

d) Are two units related?

◀ **Fig. 1** Schematic drawing of a volcano with letters corresponding to some volcanological questions that paleomagnetism and rock magnetism can help answer. PDC=pyroclastic density current. **a** Detecting volcanic ash layers in sediment cores. Magnetic susceptibility can be used to detect tephra, even cryptic tephra, from lake and ocean sediment cores due to their higher susceptibility values. **b** Emplacement temperature estimates of PDCs. If volcanic clasts in a PDC are hot during emplacement, they acquire a paleomagnetic vector parallel to the ambient magnetic field. This direction will be recorded on the clasts' magnetic vector up to the temperature (T) at which they were emplaced. Depending on how hot the PDC was, clasts will carry a single coherent component (left), two components with the lower temperature component recording the emplacement temperature (middle) or randomly oriented components (right) if the clasts were cold. Stereonets show the magnetic vector obtained during cooling within the deposit (red dots) and earlier in the clast's history (blue dots). **c** Numerical dating of volcanic deposits. The Earth's magnetic field direction (described by two angles, declination and inclination) and intensity recorded during cooling of a volcanic unit can be used for dating. This is done by comparing the components against known variations of Earth's magnetic field over relatively short time periods, called a paleosecular variation curve. The best age estimate is obtained through overlapping probability densities. Other constraints such as minimum and maximum ages or additional carbon dating can also be included. **d** Correlation of volcanic units. Rock magnetic and paleomagnetic properties can be used to correlate or differentiate different units of a volcano. In this example, statistically identical directional data for units I and II implies temporal closeness. **e** Flow direction determination. Magnetic susceptibility (K) is an anisotropic property and its tensor of second rank, for which one can determine its maximum, minimum, and intermediate values. These reflect the orientation/alignment of magnetic grains within the rock, which are affected, among other factors, by the flow of the material during emplacement. Therefore, the magnetic susceptibility can be used to determine the lava or PDC flow or dome growth direction

shows particular usefulness in young volcanic deposits when geomagnetic field behavior is well constrained and isotopic age dating techniques may either be non-viable or return high uncertainties (e.g., $^{40}\text{Ar}/^{39}\text{Ar}$, ^{14}C).

Higher precision emplacement temperature estimates

Paleomagnetic determination of emplacement temperatures of volcanic deposits has emerged as a more frequently used tool for distinguishing between hot and cold volcanic mass flow deposits (Paterson et al. 2010). Originally used simply to distinguish between a deposit that was emplaced above or below the Curie temperature of its principal magnetic minerals (Aramaki and Akimoto 1957), a more detailed technique now uses the analysis of paleomagnetic vector components to isolate different parts of the deposit's cooling history. In some cases, this method can be used to obtain numerical deposit temperature estimates (e.g., Sulpizio et al. 2008; Roperch et al. 2014; Trolese et al. 2017).

Studies have refined these emplacement temperature estimates in recent years with application to a wider variety of volcanic materials, such as millimeter-sized lithic fragments,

ignimbrites of different degrees of welding, and unconsolidated matrix of PDC deposits (e.g., Cioni et al. 2004; McClelland et al. 2004; Lerner et al. 2019b). New studies have also addressed temporal and spatial heterogeneity of peak temperature within a hot PDC deposit (Bowles et al. 2018) and the relation between juvenile and lithic clast and matrix temperatures within PDC deposits (Nakaoka and Suzuki-Kamata 2015). Paleomagnetic techniques have also been combined with other emplacement temperature techniques, like charcoal reflectance, to produce more precise temperature estimates (Pensa et al. 2018).

More detailed flow fabric studies through AMS

Prior to the twenty-first century, AMS techniques were used on lava flows and dikes to determine flow directions (Knight et al. 1986) and on ignimbrites to determine source vents and to study flow processes (e.g., MacDonald and Palmer 1990; Fisher et al. 1993; Ort 1993; Baer et al. 1997). More recent studies have seen an increase in the application of AMS for understanding flow directions and processes in lava flows and dikes, from basaltic to rhyolitic (e.g., Cañón-Tapia 2004; Porreca et al. 2015; Eriksson et al. 2015; Soriano et al. 2016; Njanko et al. 2020) and also flow and depositional processes in ignimbrites (e.g., Ort et al. 2003, 2015a; Geissman et al. 2010; Gountié Dedzo et al. 2013; Agrò et al. 2015; Haag et al. 2021). These studies are taking us past the evaluation of simple flow directions to an understanding of *how* the currents flow and deposit/freeze. They reveal previously unknown complexities of flow and the separation of depositional from transport regimes in pyroclastic density currents, the processes by which dikes form and propagate as well as how magma moves through them, and how the flow of lava varies depending on extrinsic and intrinsic factors, such as slope, mass eruption rate, and effective viscosity.

Magmatic and volcanic conditions reflected in magnetic mineralogy

Beyond the recorded magnetization vector or the physical alignment of magnetic minerals, the composition, concentration, and grain size of magnetic mineral populations commonly reflect magmatic conditions and magmatic or volcanic processes. Magnetic property measurements have the advantage of being both rapid and sensitive to micro- and nano-crystals that can be difficult to fully characterize using standard optical microscopy or even SEM. It has long been known that iron oxide assemblages are sensitive to magma composition, temperature, and oxidation state (Buddington and Lindsley 1964), as well as oxidative conditions during cooling (Tucker and O'Reilly 1980). This means that magnetic property measurements can sometimes be used to assess pre- and syn-eruptive conditions (Saito and Ishikawa

2007, 2012) and oxidative conditions during dome growth (Saito et al. 2007) or post-eruptive cooling (Furukawa et al. 2010) and hydrothermal alteration (Vahle et al. 2007). Magnetic mineralogy can be further modified by frictional heating and deformation, leading to the use of magnetic property measurements in understanding processes within volcanic conduits (Kendrick et al. 2012; Wallace et al. 2019).

Support for improved techniques from improved technology, methods, and interdisciplinarity

Many of the abovementioned applications assume the timing of magnetization acquisition or of the growth of magnetic mineralogy coincides with the eruptive event and is not related to subsequent processes. If a rock contains mixtures of distinct magnetic populations, only some of which are faithful paleomagnetic recorders, it can be challenging to isolate the desired magnetic signal. New experimental techniques allow for the magnetic “unmixing” and identification of different populations of magnetic phases (e.g., Robertson and France 1994; Heslop 2015; Lascu et al. 2015; Maxbauer et al. 2016). New, high-resolution magnetic microscopy technologies (Weiss et al. 2007; Uehara et al. 2010; Glenn et al. 2017)—sometimes combined with X-ray computed tomography (de Groot et al. 2018)—hold promise for isolating information held by individual magnetic mineral populations. These techniques may allow for the extraction of volcanologically relevant information from rocks with complex magnetization histories.

Other technological improvements increase the precision of paleomagnetic measurements and the sizes of data sets. Improved automation in superconducting rock magnetometers greatly increases the volume of samples that can be measured for a study (Kirschvink et al. 2008). This has been vital for measurement-intensive studies, like those used for creating paleomagnetic and paleointensity reference curves needed for PSV dating studies.

Recent decades have also seen an increase in the use of paleomagnetic studies as methods complementary or supplementary to other techniques in order to address questions related to volcanic processes more holistically. In particular, paleomagnetic dating techniques have been used in concert with isotopic and other dating methods to better constrain eruption ages through the dating of lava flows and PDC deposits (e.g., Bergmanis et al. 2007; Greve et al. 2016; Lerner et al. 2019a; Downs et al. 2020). Geochemical data have also been incorporated more thoroughly into paleomagnetic studies of volcanoes in order to improve spatiotemporal models of volcanic fields (Downs et al. 2018). Several magnetic techniques can be combined to resolve volcanic hazards. For example, workers have combined AMS-derived flow fabric information in PDC deposits with the temperature of emplacement to model the interaction of PDCs with urban built environments at Pompeii and Herculaneum near

Vesuvius in Italy (Gurioli et al. 2007; Zanella et al. 2007; Giordano et al. 2018).

The future of paleomagnetism and its applications in volcanology

Paleomagnetism remains an underutilized tool for volcanology. As more volcanologists incorporate these methods into their toolkit, we expect that current methods will be further refined and new methods developed, allowing new questions to be posed.

The development of new or improved regional PSV reference curves is an ongoing effort that should continue to be supported by paleomagnetists and volcanologists alike. Numerical PSV dating is currently limited by the available regional curves necessary for obtaining accurate age estimates. The sediment core sampling and laboratory work necessary for defining PSV reference curves are labor intensive and costly, but it is in the interests of the volcanology community to aggressively support these studies. The integration of diverse data sources for creating new PSV curves will be critical. The combination of high-resolution lake and marine sediment records with archeomagnetic studies and alternative sources like speleothems will be vital for improving PSV records, particularly in the Southern Hemisphere (Korte et al. 2019; Brown et al. 2021).

Recent increased focus on ethical sampling techniques recognizes that paleomagnetic coring is a destructive and often noticeable sampling technique. On occasions, it has been done in a way that damages sites that are sacred or of public interest. Future studies must strive to sample in less obtrusive ways (e.g., away from publicly visited areas), and consultation with local groups is required to avoid sampling that is disrespectful to important sites or traditions.

The rise in better data-sharing practices and archiving provides for improved sharing of paleomagnetic information. The Magnetics Information Consortium (MagIC) database accommodates both study-level directional and intensity averages as well as individual measurement data, while the GEOMAGIA50 database contains paleomagnetic (direction and intensity) and chronologic data from archeological and volcanic materials and sediments covering the past 50 ka (Brown et al. 2015a,b). Continued cataloging of these data, especially if it will be combined in the future with detailed rock magnetic data, will allow for the application of modern data analytical techniques like machine learning and numerical modeling to volcanological questions. When cross-referenced with geochemical databases, new avenues in comparative studies are opened, such as to look at similarities and differences in the evolution of magmatic provinces and settings through time, space, and composition, or to search for patterns in eruption cycles and activity within global whole Earth models.

As paleomagnetic techniques become better understood and more widely used by non-paleomagnetists, these techniques can become better integrated into multidisciplinary volcanic studies, rather than exist solely as stand-alone publications. This is evident in recent studies, in which the paleomagnetic method was used to answer an important but partial component of a broader volcanic study (Leonard et al. 2017; Stelten et al. 2018; Larrea et al. 2019). A future in which paleomagnetism is seen as a tool that can easily be used as needed to support other volcanologic approaches will produce higher quality studies aimed at addressing questions in volcanology.

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