RESEARCH METHODS VOLCANICA

Practical guide for volcano observatories on paleomagnetic sampling of pyroclastic deposits from active volcanoes

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Abstract

This brief guide is designed to teach workers at observatories of volcanoes exhibiting explosive activity how to take samples of pyroclastic deposits for paleomagnetic studies. Paleomagnetism is a powerful tool for studying volcanoes, both dormant and currently active. Studies of the rock magnetic and paleomagnetic characteristics of volcanic rocks can provide important information about volcanic deposits and the processes that deposit them. This information can include important characteristics such as emplacement temperature, age, and flow direction. To use these techniques, a specific type of sampling is required. Here we describe reasons for taking paleomagnetic samples and how to do so in the field without the use of specialized equipment.

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Volcán; Paleomagnetismo; Corriente de densidad piroclástica.

1 Introduction

Paleomagnetism is a field within geophysics that focuses on the study of the Earth's magnetic field, how it has changed over hundreds, thousands, or millions of years, and how it is recorded within natural materials [Tauxe et al. 2018]. When a magnetic mineral is cooled below a certain temperature (called the Curie temperature), it records information about the Earth's current magnetic field. Volcanic rocks typically have a mineralogical composition that includes magnetic minerals (e.g. magnetite, titanomagnetite), which is why volcanic rocks are one of the main materials for paleomagnetic studies. Paleomagnetic data has many applications within the fields of geology and geophysics; it is used to study topics ranging from tectonics and the deep Earth interior to environmental issues.

However, paleomagnetic data from volcanic rocks and deposits can also be used to study the volcanoes that produce them [Cañón-Tapia 1993; Ort et al. 2015; Lerner et al. 2022]. At an active volcano with explosive activity, this mainly involves studying pyroclastic density current (PDC) deposits and sometimes reworked deposits (e.g. lahars). Starting in the 1950s in Japan [Aramaki and Akimoto 1957], methods have been developed to analyze paleomagnetic data to evaluate PDC characteristics such as emplacement temperature, flow direction, and sometimes eruption age. These methods have been developed over the years through studies in the United States, Italy, Greece, New Zealand, Japan, and elsewhere [Hoblitt and Kellogg 1979; Kent et al. 1981; Bardot and McClelland 2000; McClelland et al. 2004; Tanaka et al. 2004]. In recent decades, these methods have come into more frequent use as a standard tool for evaluating the previously mentioned characteristics of PDCs in many parts of the world (e.g. Mexico, United States, Chile, Italy, New Zealand, Japan [e.g. Sulpizio et al. 2008; Paterson et al. 2010; Alva Valdivia et al. 2012; Pensa et al. 2018; Lerner et al. 2019b; Hasegawa et al. 2024]).

A key part of paleomagnetic studies in volcanology is stepwise thermal demagnetization, in which samples of volcanic material are heated to progressively higher temperatures and measured at each step using specialized laboratory equipment [Tauxe et al. 2018]. This process results in the paleomagnetic and temperature-related data necessary for interpreting volcanic deposits and processes. For this lab work to be undertaken, an important first step is the collection of oriented cores and/or hand samples in the field [Cañón-Tapia 2007].

This guide is meant to orient workers at volcanic observatories that may want to participate or collaborate in paleomagnetic studies to obtain important data about active volcanoes. Here we describe the reasons for conducting paleomagnetic studies, the types of data that can be obtained, and the practical steps to be followed to take paleomagnetic samples for these studies.

2 Why study PDC deposits with paleomagnetism?

Analysis of paleomagnetic data can reveal some very important characteristics of pyroclastic deposits and thus also help us understand the characteristics of the PDC processes that deposited them (see Ort et al. [2015] and Lerner et al. [2022] for reviews and examples of the techniques described below). Here are the main ones (summarized in Table 1):

2.1 Type of process: PDC or lahar?

Sometimes the physical processes associated with PDCs and lahars produce deposits with different characteristics. For example, a PDC deposit often has angular clasts and massive bedding (without internal structure), while a lahar deposit,

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Table 1: Summary of magnetic and paleomagnetic methods for studying volcanic deposits.

Method	What is it used for?	What type of samples do you need?	What field equipment do you need?	What else do you need?
Differentiation between primary and remobilized deposits	To understand if a pyroclastic deposit was emplaced during an eruption or due to secondary processes	Oriented hand simples (clasts) or oriented cube samples (matrix)	Geological compass, brush, permanent marker, hammer/spatula	Collaboration with a paleomagnetic laboratory (with a magnetometer and ovens), rock cutting/drilling laboratory equipment
Deposit emplacement temperature	To understand at what temperature a pyroclastic density current deposit was emplaced	Oriented hand samples (clasts) or oriented cube samples (matrix)	Geological compass, brush, permanent marker, hammer/spatula	Collaboration with a paleomagnetic laboratory (with a magnetometer and ovens), rock cutting/drilling laboratory equipment
Paleomagnetic dating	To understand when a volcanic deposit was emplaced	Hand samples or cores drilled from volcanic deposits	Geological compass, brush, permanent marker, hammer/spatula, specialized sampling drill and accessories	Collaboration with a paleomagnetic laboratory (with a magnetometer and ovens), high quality results with low error, regional paleosecular variation curve
Flow direction (anisotropy of magnetic susceptibility; AMS)	To find the unknown source of a volcanic deposit	Oriented samples of matrix of a volcanic deposit	Specialized paleomagnetic sampling boxes, geological compass, brush, permanent marker	Collaboration with a paleomagnetic laboratory (with specialized equipment to measure AMS)

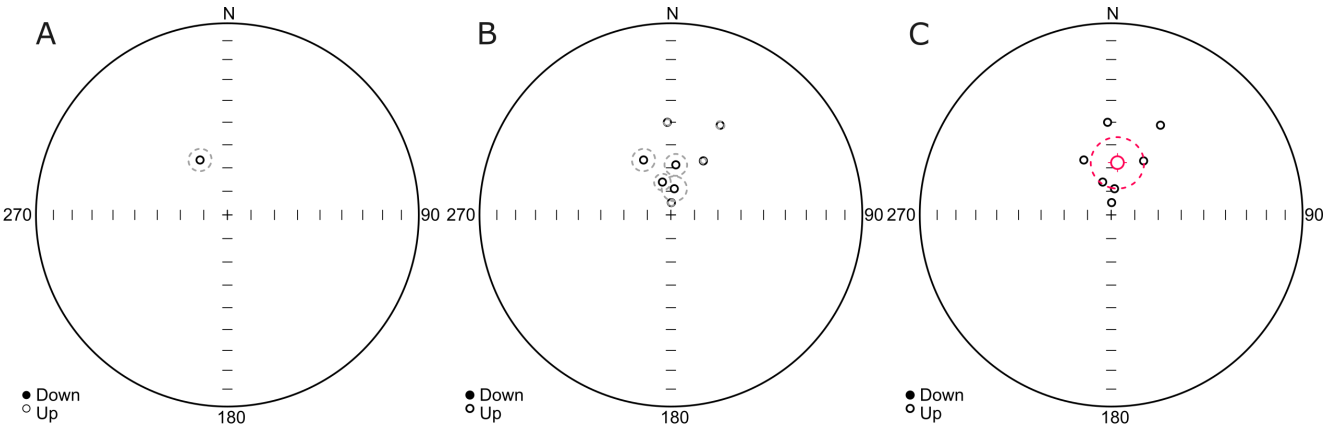

Figure 1: Stereonets representing the presentation of paleomagnetic data: [A] a stereonet showing a single paleomagnetic result representing one clast in a volcanic deposit, along with a circle representing its MAD, [B] a stereonet showing the results of paleomagnetic measurement of multiple clasts at a site, each with their own MAD circle, [C] a stereonet showing points representing paleomagnetic results of multiple clasts from a site, along with a larger point and circle representing the mean of the directions all the clasts of that site and its α95.

due to the presence of water, has laminated bedding, more rounded clasts, and a clayey/indurated matrix [Pierson et al. 2025]. However, in other situations, with pyroclastic deposits (e.g. block-and-ash flows) that are rapidly remobilized over short distances, it can be very difficult to differentiate in the field whether a volcanic deposit is primary or remobilized. By comparing data from various clasts or matrix within a volcanic flow deposit, it is possible to understand whether a deposit was emplaced directly from a high-temperature PDC during an eruption or whether it was deposited at another time by non-eruptive processes (e.g. as a lahar) [e.g. Lerner et al. 2019a].

2.2 Temperature: At what temperature was a PDC deposit emplaced?

PDCs generally have high temperatures, between 200 and 800 °C [Cole et al. 2015]. Although all these temperatures are dangerous for humans, this range 1) can result in a range of

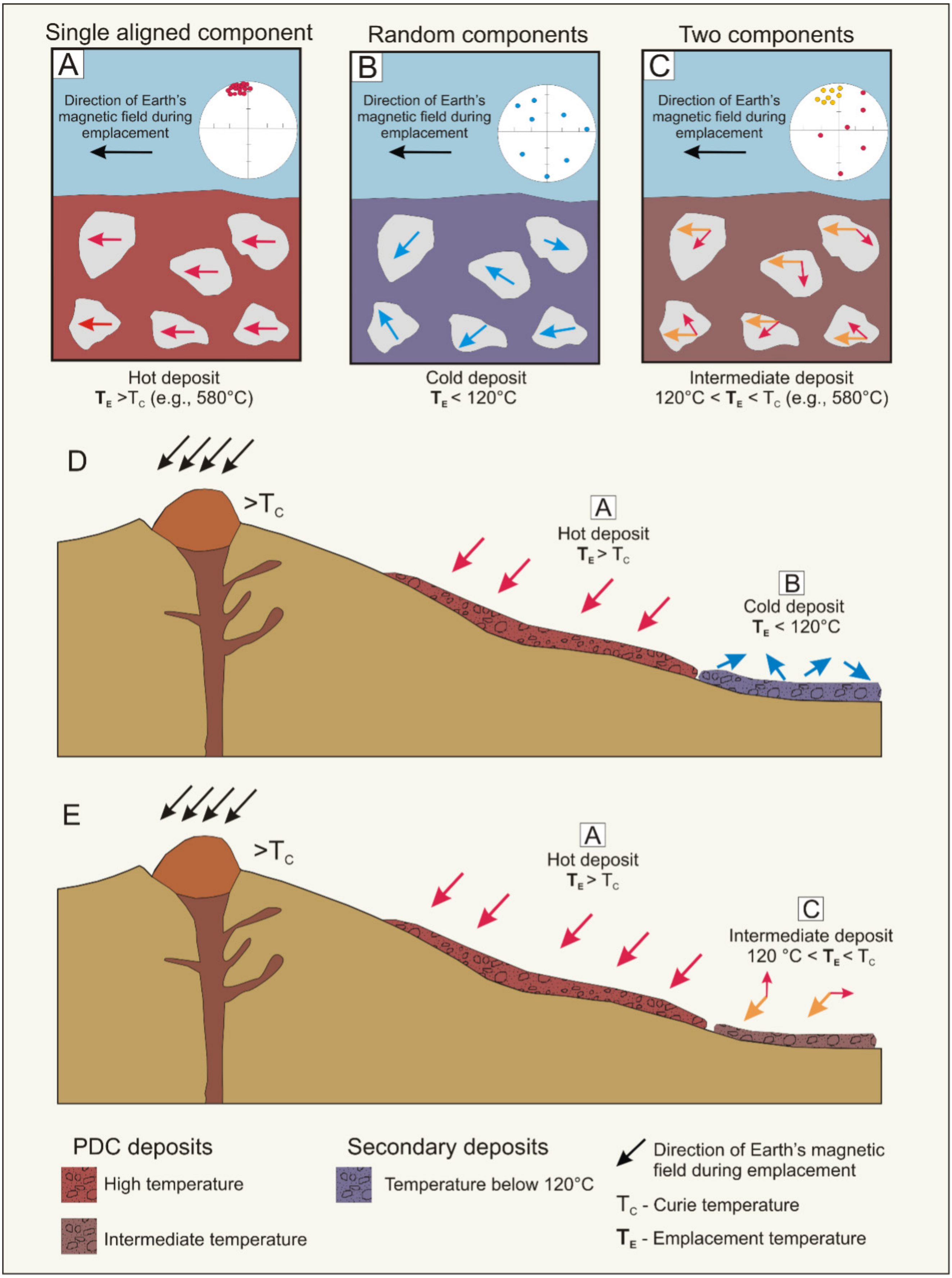

Figure 2: (Caption next page.)

Figure 2: (Previous page.) Figure representing the depositional conditions and associated paleomagnetic results for pyroclastic deposits of different cooling histories. Colored arrows represent the directional results obtained from clasts and deposits at the time of sampling. [A] PDC deposit emplaced at above Curie temperature (e.g. ~580 °C); similar paleomagnetic directional results from most clasts at each site, [B] remobilized deposit (e.g. lahar) emplaced at ambient temperature (<120 °C); random paleomagnetic results from clasts at each site, [C] PDC deposit emplaced at an intermediate temperature (between Curie temperature and 120 °C); clasts within the deposit have complex cooling histories, with at least two components of magnetic signal, high temperatures before emplacement (random results) and lower temperatures after emplacement (aligned paleomagnetic directions). [D] and [E] illustrate how these conditions would apply to volcanic deposits in the field. Modified from Lerner et al. [2022] and Uehara et al. [2015].

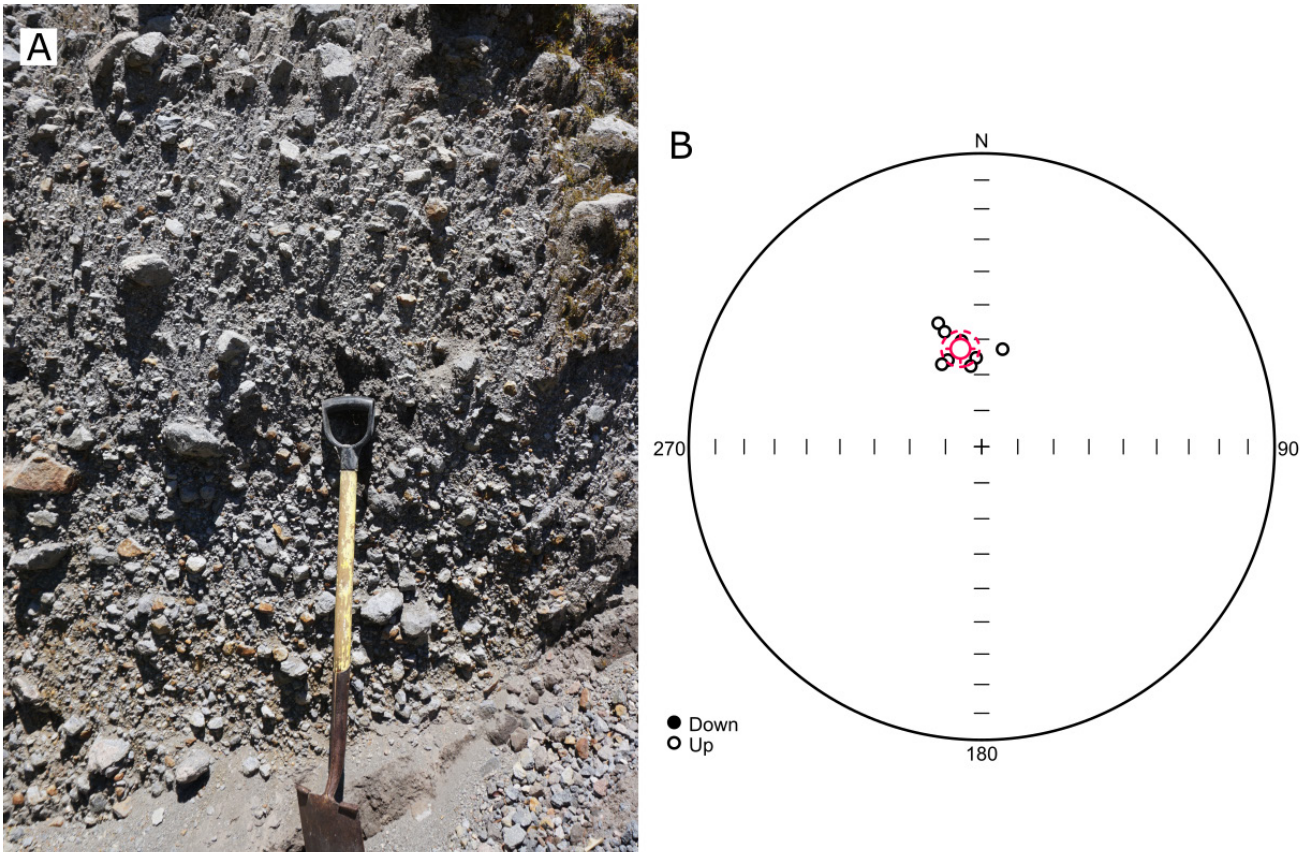

Figure 3: [A] Example of a PDC deposit emplaced at above Curie temperature (e.g. ~580 °C), [B] results plotted on a stereonet for clasts taken from a site emplaced at this temperature, showing aligned paleomagnetic directions.

different impact levels on people and infrastructure, 2) can be used to better understand the processes that caused the eruption. By studying the clasts or matrix of a PDC deposit, it is possible to understand with a relatively high degree of precision the temperature at which a PDC deposit was formed, and thus more or less the temperature of the PDC during the eruption [e.g. Paterson et al. 2010; Uehara et al. 2015; Pensa et al. 2018].

2.3 Age: When was the deposit emplaced?

In certain situations, with very high-quality data and other specific conditions, it is possible to date volcanic deposits using paleomagnetic data [e.g. Lerner et al. 2019b; Hasegawa et al. 2023; Juárez-Arriaga et al. 2025]. This is done by comparing the paleomagnetic direction recorded by volcanic material (e.g. lava flows, ballistic projectiles, or the clasts or matrix of a PDC deposit) with the history of changes in the Earth's magnetic field in a region (paleosecular variation). This technique has varying levels of precision highly dependent on data quality and quantity and is constrained by existing paleomagnetic data within a region (frequently local paleosecular variation data does not extend beyond the Holocene). The minimum α95 (uncertainty, see below) of a paleomagnetic site mean direction is typically at least 1–2°, and the Earth's geomagnetic direction changes on average about 0.1° per year, meaning that the time resolution of this method is tens of years at best [Speranza et al. 2006]. As such, this method is most useful for studying deposits from pre-historic eruptions and eruptions separated by significant amounts of time. For eruptions separated by only months or years, it is very unlikely to obtain clearly differentiated dates.

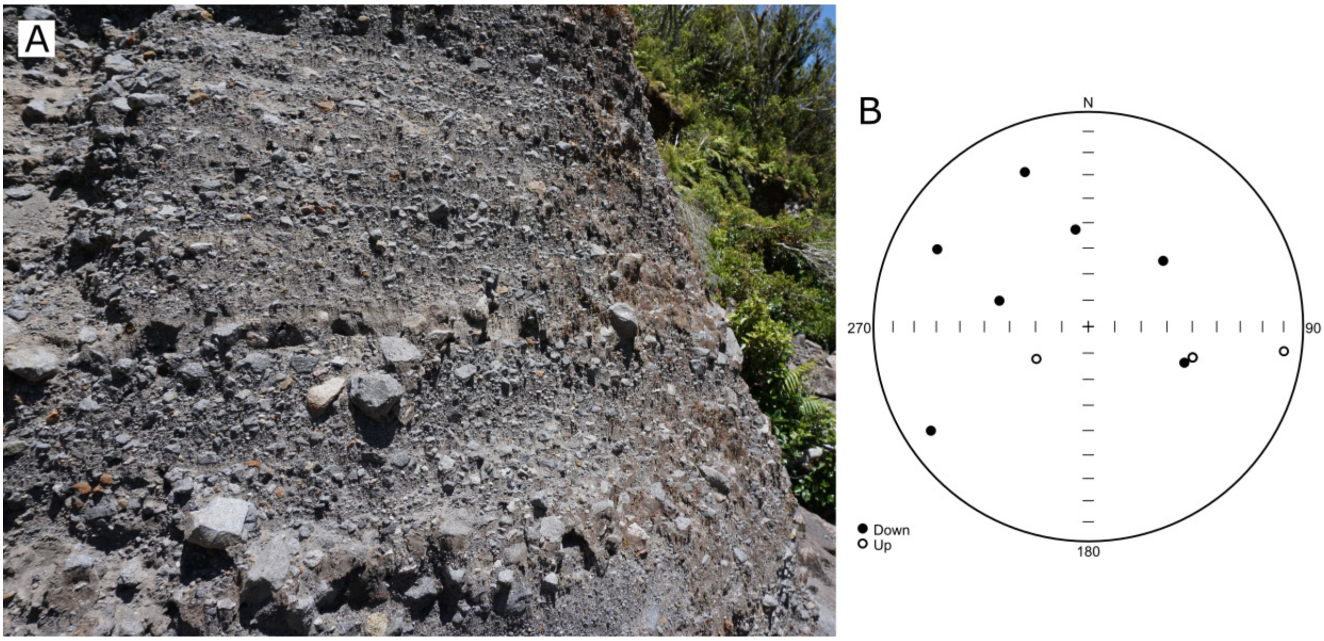

Figure 4: [A] Example of a remobilized deposit emplaced at near ambient temperature (<120 °C), [B] results plotted on a stereonet for clasts taken from a site emplaced at this temperature, showing random paleomagnetic directions.

2.4 Direction: Where did the deposit come from?

By using a rock magnetic technique called anisotropy of magnetic susceptibility (AMS), it is possible to study the flow dynamics and direction of a volcanic deposit (such as lava flow or PDC) by observing the alignment of the magnetic minerals it contains [Ort et al. 2015]. This technique is used to understand the most likely flow direction of a volcanic deposit when it was still moving. This technique is used when the source of a prehistoric eruption is unknown—by studying the flow direction from various points using the matrix of a deposit, it is possible to locate the vent and to understand flow and depositional conditions [e.g. Ort et al. 1999; 2003].

3 How does the paleomagnetic method for studying emplacement temperatures of volcanic deposits work?

Given that at a frequently active volcano the timing and source of eruptions will generally be known, we will focus on the method for determining the type and emplacement temperature of volcanic deposits. This method works by comparing paleomagnetic directions recorded by various clasts within a pyroclastic deposit. The concept of this method is originated from the "conglomerate test" in paleomagnetic study generally applied to sedimentary rocks [Graham 1949]. When a rock cools below a certain temperature (called the Curie temperature), the rock's magnetic minerals record a signal of the Earth's magnetic field (a paleomagnetic signal) at the time of cooling [Tauxe et al. 2018].

The Curie temperature depends on the magnetic minerals in the rock; that of magnetite (the most common magnetic mineral in volcanic rocks) is generally around 580 °C, while less common magnetic minerals have higher (e.g. hematite; 620 °C) or lower (e.g. ilmenite; 200–400 °C) Curie temperatures. Because rocks can contain more than one magnetic mineral phase, it is common that more than one Curie temperature is represented in the rock's magnetic characteristics and behavior.

The paleomagnetic signal is recorded in the form of vector data. That is, the data has a three-dimensional direction (paleomagnetic direction) and a strength value (paleointensity). The paleomagnetic direction is reported with two measurements, representing the horizontal (a measure of declination from 0–360°) and vertical (a measure of inclination from 0–90°) parts of the vector. Each paleomagnetic measurement also has a value called maximum angular deviation (MAD; represented in degrees), which represents the level of uncertainty associated with our data. The intensity is reported as a magnetic field strength value, usually in microTesla (μT). So, a complete vector measurement of paleomagnetic direction and paleointensity looks like this:

$$XXX^\circ, YY^\circ, \mathrm{MAD} = x^\circ, Z\ \mu\mathrm{T}, \quad (1)$$

where XXX is the declination, YY is the inclination, x is the maximum angular deviation, and Z is the intensity (e.g. 034°, 27°, MAD = 2.1°, 43 μT).

The directional part of these data can be represented on a stereonet, which shows the projection of our direction (and its MAD) onto half of a sphere (Figure 1A). Multiple paleomagnetic results can be plotted on the same stereonet to compare the results of various paleomagnetic samples (Figure 1B), and if the samples are related, we can calculate a mean direction (with its own uncertainty, called α95) of the vector data from all of the samples (Figure 1C). In general, a collection of 6–8 clasts is ideal for measuring a site mean from a PDC deposit, but this can vary depending on the study goals and sampling

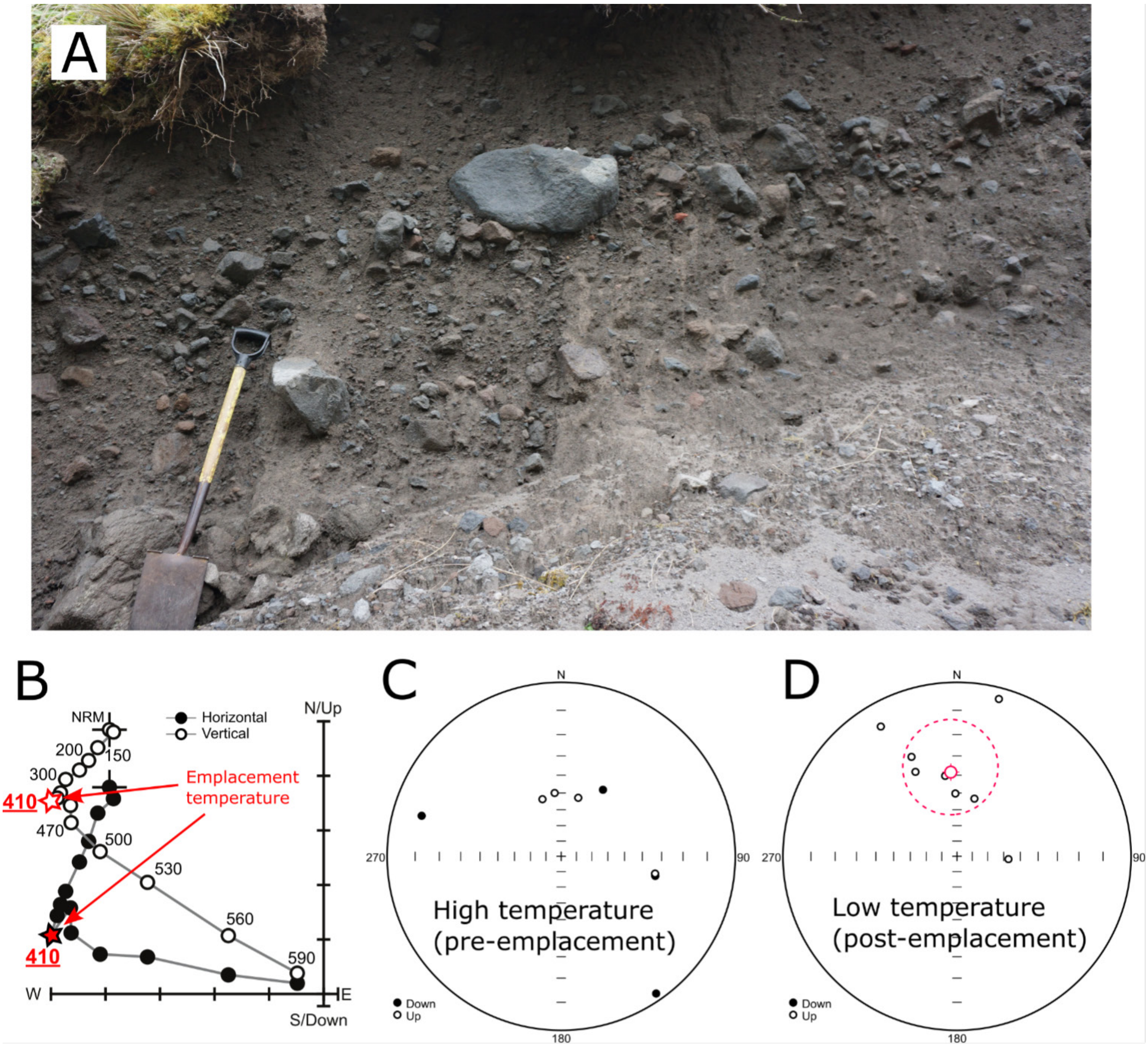

Figure 5: [A] Example of a PDC deposit emplaced at an intermediate temperature (~120–580 °C), [B] vector component diagram for a clast emplaced at an intermediate temperature. Numbers represent temperature (in °C) corresponding to cooling during and after emplacement and to demagnetization temperatures in the laboratory. Two components of the remanent magnetization can clearly be seen, with the point where they meet representing the emplacement temperature, [C, D] results plotted on stereonets for clasts taken from a site emplaced at this temperature. In this scenario, the results representing each part of the cooling history are reported on separate stereonets, a stereonet [C] representing the pre-emplacement, high temperature cooling history (random directions) and a stereonet [D] representing the post-emplacement, low temperature cooling history (aligned paleomagnetic directions).

material available at a given site (see Sampling methods Section 5 below).

For this method, data representing the paleomagnetic direction of the clasts is combined with our knowledge of important characteristics of volcanic processes to evaluate what the temperature of a volcanic flow was at the time of its emplacement. There are three possible scenarios that we can encounter when applying this method to a deposit (Figure 2):

1. **A deposit emplaced above Curie temperature (e.g. ~580 °C for magnetite):** In this case, we are looking at a PDC deposit emplaced through primary volcanic processes (Figure 2A, 3A). This means that during the eruption, most of the material in this deposit descended the volcano at high temperature, sometimes picking up additional material that was then heated due to being part of the PDC. All of the material (clasts and matrix) of this deposit was emplaced together at this high temperature and cooled together in the same magnetic field (i.e. all the material has the same cooling history).

Any material that was picked up by the deposit is heated until it meets the temperature of the rest of the deposit that is cooling (this is called the equilibrium temperature). From a paleomagnetic perspective, what that means is that when we sample several clasts from this deposit and conduct paleomagnetic measurements, we should get similar results (i.e. similar paleomagnetic directions) from all of these clasts (Figure 2B). This can be represented on a stereonet, where we will see a statistically significant grouping of the results from clasts taken at a single, independent site within the deposit (Figure 3B).

2. **A deposit emplaced at or near ambient temperature (approx. <120 °C):** In this case, we are looking at a deposit made up of material that was emplaced at a low temperature after undergoing most or all of its cooling in a different location (Figure 2B, 4A). This means that between the time of cooling (and with it the acquisition of the associated magnetic direction of Earth's magnetic field at that moment) and the present, all of the material in the deposit was physically moved and rotated before forming the deposit we see in the field. Even if some or all of our deposit material may have previously shared a cooling history and magnetic direction, the physical reworking of the material has randomized the orientation of the clasts. When the paleomagnetic directions of all the sampled clasts are measured, there will be no meaningful grouping of the results (Figure 2B). On the stereonet, we will see a statistically random presentation of our data (Figure 4B).

3. **A deposit emplaced at an intermediate temperature (above ambient temperature but below Curie temperature):** PDC deposits can also be emplaced at intermediate temperatures (e.g. 350 °C). In this case, our deposit consists of material that may have cooled partially in another location before its final emplacement or resulted from a lower temperature PDC (Figure 5A). Samples from this deposit will present a more complex result, as the clasts will contain a magnetic signal that represents (at least) two parts of the cooling history: before and after final emplacement (Figure 2C). This can be seen in a paleomagnetic plot called a vector component diagram, which breaks our vector direction into its horizontal and vertical components and allows us to see how complex the cooling history of each sample is (Figure 5B). This also means that when comparing the paleomagnetic directions for sites whose clasts display multiple components of cooling history, we use multiple stereonets: one representing the high temperature component of the magnetic signal (acquired before final emplacement) and one representing the low temperature component of the magnetic signal (acquired during cooling at its final location of emplacement) (Figure 5C, 5D). At high temperatures, each of the clasts may have a different cooling history and has also been physically moved before its final emplacement, so this stereonet will show a statistically random result (Figure 5C). However, following the deposit's final emplacement, all of the clasts in the deposit cooled together, meaning that the stereonet representing the low temperature portion of the cooling history will show well-grouped directions (Figure 5D). The point representing the change between the high and low temperature components of the magnetic signal, which can be identified on the vector component diagrams (Figure 5B), represents the estimated emplacement temperature of each clast in our deposit. With temperature estimates from various clasts within our intermediate temperature deposit, we can estimate an overall emplacement temperature range of the deposit.

4 What kind of results does the paleomagnetic emplacement temperature method give?

The results of this method will depend on the type of deposit sampled, but will come in two categories:

1. Differentiation between the three main categories of deposit. Each site sampled will result in a stereonet showing the paleomagnetic direction of each clast sampled at the site, which can be used to decide if the deposit was emplaced at a high, intermediate, or low temperature.

2. Emplacement temperature estimates for each clast sampled within a high temperature or intermediate temperature deposit. Each clast can be evaluated using a vector component diagram to estimate a precise emplacement temperature in the case of intermediate deposits or minimum emplacement temperature in the case of high temperature deposits. The temperature estimates of all the clasts at a deposit can be evaluated to estimate an overall emplacement temperature for the deposit.

These results, combined with a volcanological analysis of the deposits in the field, can be used to make interpretations of the origin of the deposits and the dynamics of the flows that emplaced them.

5 Sampling procedure

5.1 Types of samples

The type of samples collected for this method are generally oriented hand samples. In most uses of this method, lithic clasts (i.e. fragments of rock drawn from a lava dome or the volcanic edifice and incorporated into the PDC) are generally preferred, however, other materials like pumice, ash matrix, or even archaeological materials, may also be used depending on the exact goals of the study [e.g. Cioni et al. 2004; McClelland et al. 2004; Bowles et al. 2018; Lerner et al. 2019a]. These samples will be used to create laboratory specimens that can be demagnetized and measured in the laboratory. These specimens are generally in the form of 25 mm diameter, 25 mm-long rock cylinders (Figure 6A), or 2 × 2 × 2 cm rock or ash matrix cubes (Figure 6B–6C). Since the data generated by paleomagnetic measurements are vectors representing a 3-dimensional direction of the Earth's magnetic field as recorded by the rocks we sample, it is critical that we understand the physical orientation the samples had when they were still part of the outcrop. Therefore, there are some key characteristics that hand samples taken in the field must have:

1. Are big enough that drilling or cutting them into specimens will yield at least one (ideally two or more) cylinder or cube. Generally, a fist-sized clast (around 5–10 cm in diameter) is ideal (Figure 6D),

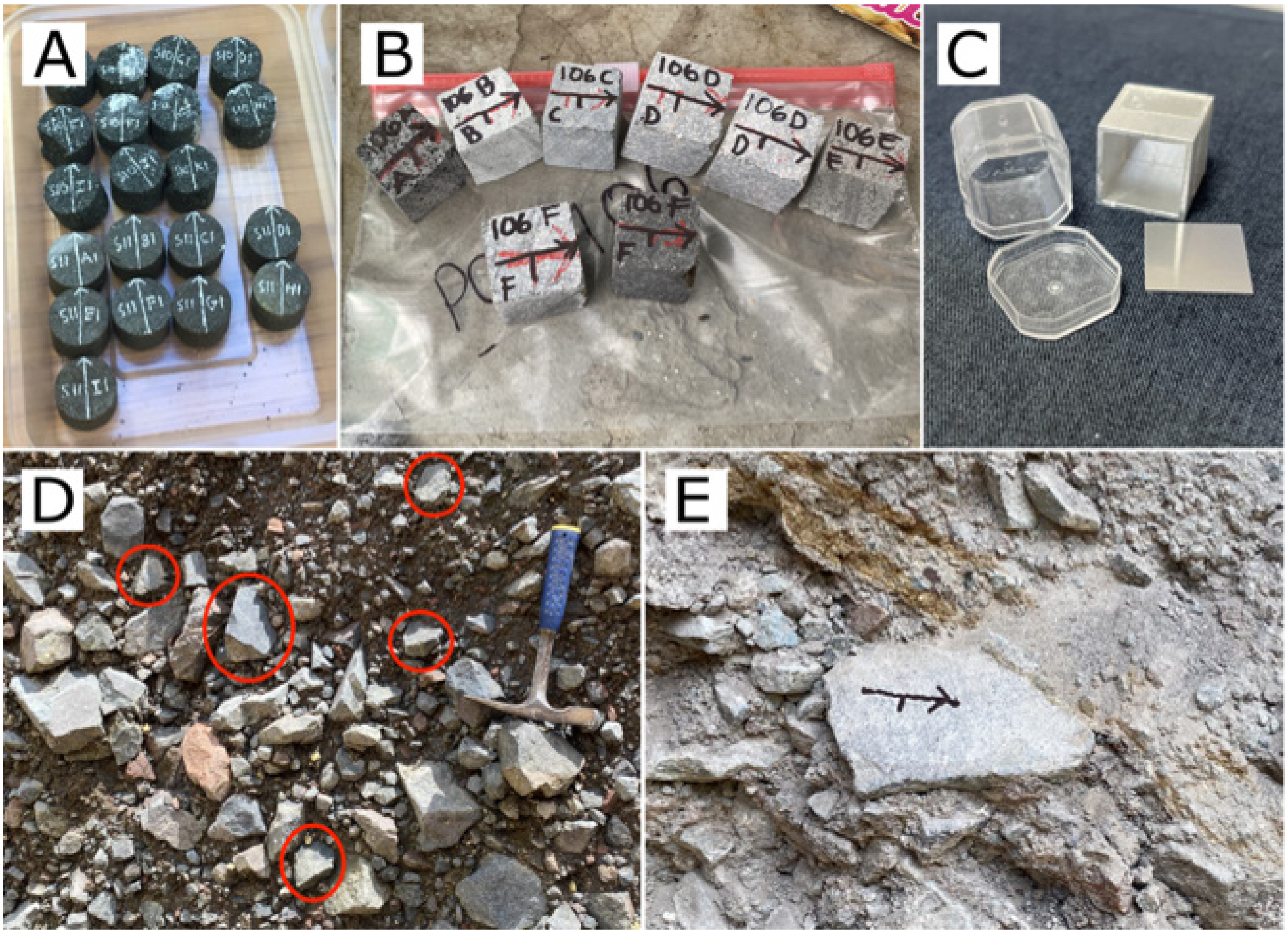

Figure 6: Photos showing important paleomagnetic sample and specimen characteristics. [A] example of 25 mm diameter, 25 mm-long cylindrical rock specimens, [B] $2 \times 2 \times 2$ cm rock cube specimens, [C] specialized plastic and metal boxes for collecting $2 \times 2 \times 2$ cm cubic samples of ash matrix, [D] PDC outcrop with several viable hand samples highlighted, [E] example of an ideal hand sample, note the flat face of rock that is ideal for measuring and labeling.

2. Are still in situ within the outcrop in which it is deposited (i.e. exactly in its original place of deposition; not taken from parts of the deposit that appear to have moved since emplacement or from the ground nearby, even if it clearly originates from the same outcrop) (Figure 6D),

3. Have a flat surface that can be oriented and labeled (Figure 6D),

4. Are oriented with a geological compass and labeled in the field *before being removed from their outcrop* (Figure 6E).

5.2 Equipment

The equipment needed for most types of sampling of pyroclastic deposits is relatively simple and can be relatively easily carried by one person. The primary tasks to be accomplished are identifying clasts to sample, orienting and marking the sample, removing the sample from the outcrop, and further cleaning and labelling each clast. To accomplish this, the following equipment is recommended:

- Field notebook (Figure 7A)—for recording paleomagnetic sample orientations, site name and coordinates, and geological observations;

- Brushes (Figure 7B)—for cleaning the sample before labeling; it is important that the sample is relatively clean so that the orientation arrow and labels do not rub off;

- Permanent markers (Figure 7C)—for labeling the sample orientation and name; those that do not easily rub off or smudge, even when wet or dirty. Ideally many, as markers wear down quickly, especially if the rock surfaces are covered in ash, and do not label as precisely once blunt;

- Geological compass (Figure 7D)—for orienting clasts before removing from the outcrop; a compass with a level and a clinometer that is capable of taking both a horizontal (azimuth) and vertical (dip) measurement;

- Smartphone compass-clinometer application (Figure 7E)—many modern smartphones have internal hardware sufficient to take precise orientation measurements using a number of available applications. Before deciding to use a

Figure 7: Key equipment for paleomagnetic sampling of pyroclastic deposits: [A] Field notebook, [B] brushes of varying sizes for cleaning rock samples before labeling, [C] permanent markers for labeling, [D] example of a geological compass-clinometer for orienting samples, [E] example of a smartphone compass-clinometer app that can also be used for sample orientation, [F] metal spatulas of varying sizes for cleaning the outcrop and the samples, [G] geological hammer/pick for cleaning the area around the sample and removing the sample from the outcrop, [H] cloth and plastic sample bags for organizing oriented samples.

smartphone for orientation measurements, it is advisable to test the phone app against a geological compass to ensure that the measurements are accurate;

- Metal spatulas (Figure 7F)—useful for cleaning the samples and removing matrix from around the sample to allow easier measurement of the orientation;

- Hammer/pick (Figure 7G)—for cleaning the area around the sample, removing the sample from the outcrop, and potentially breaking a sample that is larger than expected once removed from the outcrop;

- Sample bags (Figure 7H)—either large freezer bags (made from thick plastic to avoid tearing due to pointed sample edges) or cloth bags (e.g. reusable shopping bags) are useful for organizing the group of clasts taken from a single site.

5.3 Site selection

The process of site selection depends on type of eruption and deposit, but in general the goal is to collect independently oriented samples at a series of independent sites. *Independent* means that each site is geologically/geographically independent and therefore not influenced by the cooling and emplacement history of other sites, and that each sample is oriented individually, and therefore not dependent on the orientation of other samples. By following this selection protocol, when one specimen from each sample is measured in the lab, each paleomagnetic direction measured can be used to evaluate a site, and all the sites can be compared to evaluate the deposit as a whole.

Where possible, it is useful to select sites that may represent different cooling histories from the same eruption. This can mean sampling at different distances from the volcano within the same channel, within various channels or locations laterally around the volcano (if the pyroclastic deposit is not contained to a single channel), and at different heights within a deposit (if the deposit is of significant thickness). Sampling various pulses of the same eruption (if the events or deposits suggest emplacement in pulses) is also effective for capturing

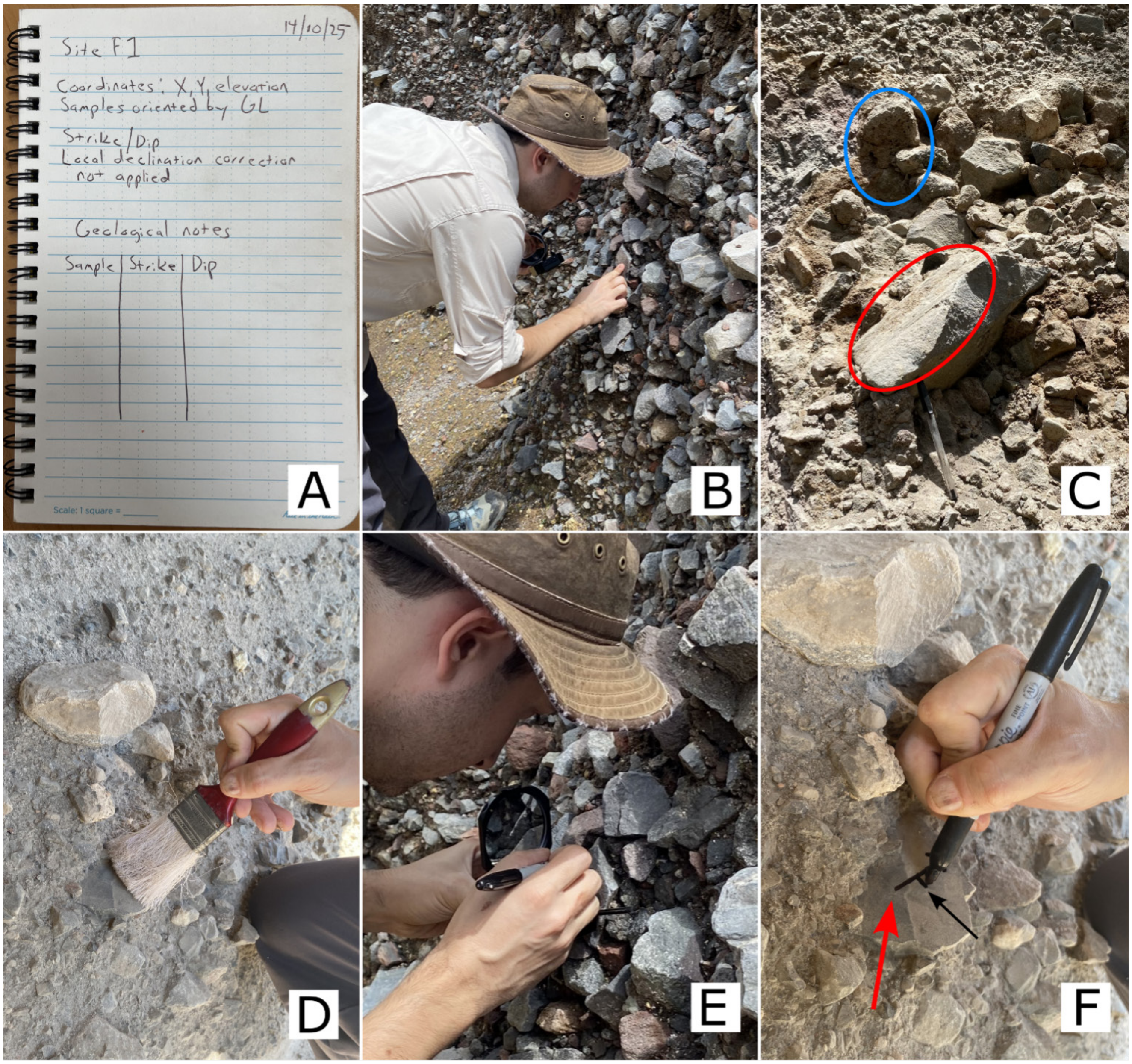

Figure 8: Steps for taking oriented paleomagnetic samples from a pyroclastic deposit outcrop. [A] Example of a field notebook page prepared for notes on sampling and orientation, [B] examining the outcrop to choose ideal clasts for sampling, [C] example of an outcrop with a clast dipping away from the outcrop circled in red and an a clast with an inverted flat surface circled in blue, [D] cleaning the surface of a sample and clearing space around it before orientation and labelling, [E] using a permanent marker to draw a strike arrow parallel to the measurement being taken by the compass, [F] clast with the orientation arrow drawn for strike (indicated by red arrow) and tick mark for dip (indicted by smaller, black arrow). (Continued next page)

the cooling history of deposits from different parts of the eruption.

When the goal of the study is to differentiate between primary and remobilized deposits, sites should be chosen where this uncertainty exists. When the goal is to estimate the emplacement temperature of identified PDC deposits, sites should be selected based on the certainty that they are primary rather than remobilized.

5.4 Sampling at the outcrop

Once you arrive at the outcrop with the necessary sampling equipment, the procedure for sampling is relatively straightforward:

1. Prepare your notes—The simplest way to organize paleomagnetic sample information is a three-column table with headings for sample name and orientation measurements (Figure 8A). It is useful to include any relevant information about the sampling, including who is taking the samples, the orienting convention that is being used (e.g. strike and dip, dip

Figure 8: (Continued from previous page) [G] measuring the strike of the sample with the geological compass, [H] measuring the strike and dip of the flat sample face with a smartphone compass-clinometer app, [I] example of a standard field notebook table with sample names and orientations, [J] oriented sample being labeled with its sample name after removal from the outcrop, [K] samples from a single site organized together in a well-labeled sample bag.

and dip direction, etc.), if the local magnetic declination correction is already accounted for or will need to be accounted for (this depends on your location and your orienting tool). It is also ideal to include the complementary geographical and geological information about each site, including coordinates, outcrop observations like height, number of layers, color, sorting, rounding, etc. It is also recommended to take photos of the outcrop to document the important features of the deposit. Paleomagnetic site names generally consist of a prefix related to the project (shorter is better for labelling purposes) and a site number in the order of collection. For example, F1, F2, F3 or FG1, FG2, FG3 (Fuego site 1, Fuego site 2, Fuego site 3), or F25-1, F25-2, F25-3 (Fuego 2025 site 1, etc.).

2. Identify clasts for sampling—The ideal lithic clasts are around fist-sized and, critically, have a relatively uniform flat face that can be oriented (Figure 8B). For easier orientation, try to find clasts whose flat surface dips away from the outcrop (i.e. the flat surface should not be inverted) (Figure 8C). Select approximately 6–8 clasts suitable for sampling. This will generally result in a sufficient amount of data for paleomagnetic analysis. In cases where you know that very few sites will be sampled (e.g. deposits from the eruption of interest have mostly already eroded or are not safely accessible), it can be beneficial to take more samples. In cases where very few suitable samples can be identified at an outcrop (e.g. few clasts, clasts not angular enough, time or safety constraints) it is still worthwhile to sample if 4–5 clasts can be identified.

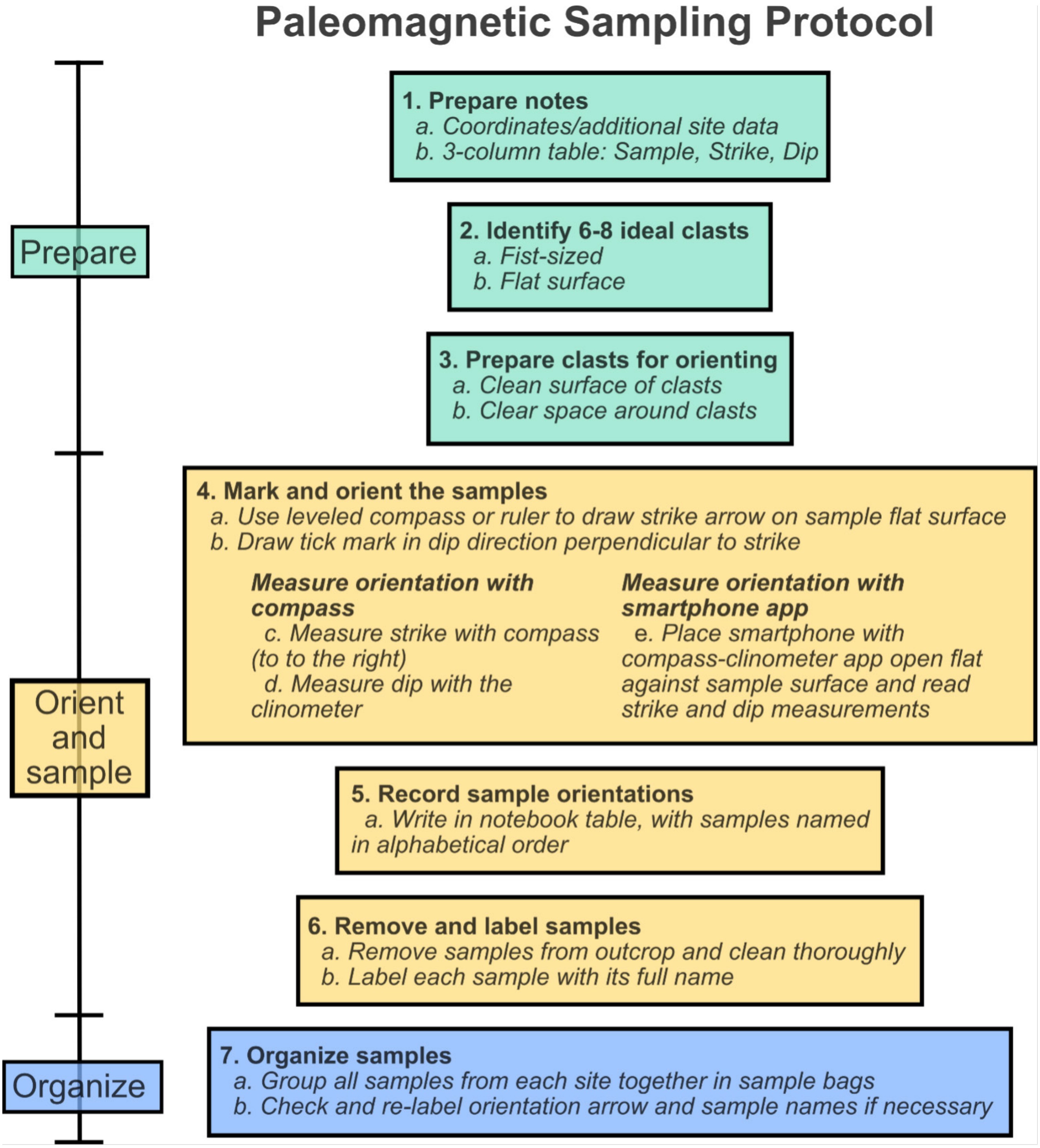

Figure 9: Brief, visual paleomagnetic sampling protocol. The seven steps are coordinated with the more detailed descriptions of the sampling procedure in the text, and the relevant photos for each step can be seen in Figure 8.

3. Clean the clasts and make space for orienting (Figure 8D)—Clean the surface of the clast that will be oriented (with brushes and spatulas) so that the orientation arrow can be clearly written. If necessary, remove material from around the clast (without moving or dislodging the clast itself) to create enough space to use your compass or phone for orienting.

4. Orient and mark the sample—If using the compass, level the compass to take a strike measurement of the exposed flat face of the sample (generally strike is taken to the right). Without moving the compass, use your marker to draw an arrow parallel to the strike on the rock (use the edge of your compass that is in contact with the rock as a guide) (Figure 8E). Draw a tick mark on the arrow in the direction of the dip of the

oriented face (Figure 8F). Use the clinometer of your compass to measure the dip of the oriented face (Figure 8G).

4a. If using a smartphone app, use a level ruler or a geological compass to draw the strike line (arrow to the right) on your sample (Figure 8E). Draw a tick mark on the arrow in the direction of the dip of the oriented face (Figure 8F). Place the smartphone with the app open flat against the sample so that the plane of the phone is parallel with the flat face of the rock (Figure 8H). The app will provide both the horizontal and vertical orientation (e.g. strike and dip) measurements at the same time.

5. Record the sample orientations—Each orientation should be recorded in the table in the field notebook, with samples labeled by letter in alphabetical order (e.g. F1A, F1B, F1C, for Fuego site 1 sample A, Fuego site 1 sample B, etc.) (Figure 8I).

6. Remove samples from outcrop and label them—Use spatulas, pick, etc. to remove each oriented sample from the outcrop, and label them with the letter that corresponds to their recorded measurement in the notebook (Figure 8J). Use brushes, etc. to clean the samples if necessary to ensure the label is clearly written.

7. Organize samples and ensure quality of labelling—Store all samples from a single site together in clearly labeled plastic or cloth sample bags (Figure 8K). Before storing the samples, ensure that the samples have been cleaned and labeled or relabeled as clearly as possible, in multiple locations, to ensure that the label and orientation arrow do not get smudged or erased during transport and storage. Occasionally clasts will turn out to be bigger than expected once removed from the outcrop. If possible, these clasts can be broken to a more reasonable size, *as long as the marked orientation arrow is preserved and enough oriented material remains to cut or drill a specimen in the lab.*

The sampling protocol is summarized in Figure 9. We recommend printing this figure and bringing it in the field to have a quick, visual version of the sampling procedure for reference. A video guide is available in Supplementary Material 1.

6 Next steps

At this point, the process should be repeated for as many sites as necessary depending on the goals of the study. A detailed study of a single eruption or deposit will ideally involve the collection of samples at many sites in different locations, depths within the deposit, or pulses of an eruption, as previously mentioned, while a study of multiple eruptions over time might involve as few as one site from a single eruption depending on the existence, accessibility, and safety of sampling sites (e.g. in a currently active volcanic area).

The samples must be transferred to a collaborating paleomagnetic laboratory, where the clasts can be cut or drilled to create paleomagnetic specimens. These can be measured with a magnetometer to determine their paleomagnetic direction and possibly with other magnetic equipment to determine other key rock magnetic characteristics (e.g. Curie temperature, hysteresis properties). This will provide the data necessary for analysis to determine deposit types and emplacement temperatures.

7 Concluding remarks

The application of the sampling protocol and paleomagnetic methods discussed in this guide can provide us with important information regarding PDC emplacement temperature and can also be useful for differentiating between deposits that cannot be effectively distinguished in the field (primary versus secondary deposits). This is useful for gaining a better understanding of the physical properties which govern PDC emplacement at frequently active volcanoes. Additionally, these studies provide information that can complement other studies and observations of eruptive activity. Although research scientists and those that work at observatories do not always have the same priorities and responsibilities, the use of these methods for the study of frequent explosive eruptions can result in useful data for both fundamental scientific study and practical purposes. The experience and knowledge that observatories have of their volcano(es) and its recent deposits, in combination with the paleomagnetic expertise, resources, and laboratory equipment of research institutes and universities, can provide the foundation for conducting fundamental and innovative collaborative studies. These short- and long-term studies of the dynamic and hazardous properties of PDCs and lahars are extremely useful for improving our understanding of the processes involved and for the work carried out at volcanological observatories in relation to the monitoring, planning, and mitigation of explosive eruptions.

Author Contributions

GAL wrote the first draft in English and Spanish. RMLB edited the Spanish version of the manuscript. Both authors contributed to the production of figures, collection of field photos and videos, and the editing of the final version of the guide.

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Data Availability

No new data was created or collected for this guide.

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