International Journal of Geoheritage and Parks 12 (2024) 396–415

Contents lists available at ScienceDirect

International Journal of Geoheritage and Parks

journal homepage: http://www.keaipublishing.com/en/journals/international-journal-of-geoheritage-and-parks/

Creating a sense of intangible science: Making it understandable to a broad public via geoheritage

Rasia Shajahan [a,*], Benjamin van Wyk de Vries [b], Elena Zanella [a], Andrew Harris [b]

[a] *Dipartimento di Scienze della Terra, Università degli Studi di Torino, Via Valperga Caluso 35, 10125 Torino, Italy*
[b] *Université Clermont Auvergne, CNRS, IRD, OPGC, Laboratoire Magmas et Volcans, 63000 Clermont-Ferrand, France*

ARTICLE INFO

Article history:
Received 28 November 2023
Received in revised form 15 July 2024
Accepted 16 July 2024

Available online 25 July 2024

Keywords:
geosites
inventory
anisotropy of magnetic susceptibility
modified geosite assessment model
science communication

ABSTRACT

Scientific studies, their methods and results are often difficult to understand for non-specialists due to their esoteric nature. Such lack of understanding means that such work is removed from our normal life experience, and thus, the applicability, interest and use of such work can be minimal. The communication of geoscience finds a natural conduit through geoheritage. A good example of an inaccessible technique far removed from everyday experience is anisotropy of magnetic susceptibility (AMS), an extremely useful geoscience technique with many applications, including finding strain and flow directions in rocks. We explored here how to make "AMS" understandable, using three different volcanic sites where the flow of molten rock is an important aspect, each situated in different types of geoheritage visitation context (wild trekkers, beach visitors, and walkers). The method we developed and tested follows the production of simple and adapted explanations, and is coupled with geoheritage inventorying and communication. We utilized the tangible geological features of outcrops, as well as intangible elements such as rock magnetic data, and conducted a geoheritage inventory using the modified geosite assessment model (M-GAM) method to create narratives for popular comprehension. The M-GAM analysis has identified the geosites of the San Bartolo lava flow of the Stromboli volcano for the communication of the AMS. Later, a simple and comprehensible definition of AMS and thus of the flow processes was created using a step-by-step process. This method could be useful for scientific studies to allow them to reach out to a wider public, using their input in the simple explanation stage to con-construct a narrative. This would provide a way for science to be more widely appreciated, useful and applicable.

1. Introduction

Scientific information is often arcane, clouded in jargon, or marked by complex formulations. Such information is typically generated by esoteric scientific communities or, in some cases, inherently comprises difficult and intricate subjects and techniques. This situation blocks a greater understanding of the science by a wider community, reducing its usefulness and its impact. It can even generate distrust and rejection of ideas and scientists. It can also inhibit new ideas that might grow from a wider airing of the subject, as the more widely concepts are discussed, the more general inspiration can be generated.

* Corresponding author.
E-mail address: rasia.shajahan@unito.it (R. Shajahan).

https://doi.org/10.1016/j.ijgeop.2024.07.007

One way to open up science and break down barriers is to use day-to-day features in normal life, which is the object of scientific study. In geosciences, the outcrop is the primary object, and rocks form part of most people's daily life, in one way or another. The description and communication of such outcrops is geoheritage. Geoheritage provides methods that link geosciences and society. This link, through the use of such geosites, can be used to deal with esoteric problem. We explore this with a particularly intangible arcane subject, anisotropy of magnetic susceptibility (AMS). We develop a simplified way of explaining it, combine this with a geoheritage inventory for three sites, and then explore how to present AMS to the public.

AMS is a rapid and effective scientific method used to find the orientation of magnetic minerals, and this indirectly can be used to infer the past flow of rocks. Simply put, AMS can be defined as a magnetic pointer that shows the direction that magnetic minerals point to. AMS has been used in different fields, including structural geology, tectonics, volcanology, sedimentology, oceanography and palaeomagnetism (Bouchez, 1997; Fuller, 1963; Graham, 1954; Granar, 1958; Kent & Lowrie, 1975; Khan, 1962; Zhu et al., 2012). In addition to these fields, magnetic susceptibility is used in environmental pollution studies (Bityukova et al., 1999), paleoclimate studies (Li et al., 2020) and paleoenvironmental studies (Ellwood, 1980; Matasova et al., 2001).

Even though AMS is one of the most widely applied techniques in geoscience, the concept is very difficult for people to grasp, even for those from the scientific community, and AMS researchers have difficulty in communicating their method. We carried out AMS work in order to develop and test a communication method in the context of geosite.

A geosite is a site of geological interest that, in many cases, can be part of popular culture, and can be a valuable touristic destination for people both locally and internationally (Dowling, 2011; Suzuki & Takagi, 2018). Examples of such geosites are the Grand Canyon National Park in USA, the Anashauyco Quarries of Arequipa in Peru, Tana Island in the Pacific State of Vanuatu, or the Afar Depression in Ethiopia. These are all International Union of Geological Sciences (IUGS) Geological Heritage sites.

Geosites form the basic building blocks for the geological significance of UNESCO Global Geoparks.[1] Many states now have national geoheritage inventories of geosites that are strongly based on their scientific importance. Also, geosites are used widely to transmit geoscientific information, usually with interpretation panels, supporting literature and guides. This is the environment in which arcane science can be included and gain more understandability.

While many geosites are recognised principally for their scientific values, more than half of the tourists who visit them do so for their aesthetic or scenic values (Allan et al., 2015). Science is, thus, generally not the most interesting part of such sites for the general public. This could be because science is only part of a site's significance (something not always appreciated by the scientist), but it is also because scientific communication is often poorly adapted to a broad audience. Even when people try to seek out and understand scientific information concerning the place they are about to visit, the scientific content they might find is often mostly scientific papers, which are clearly difficult for a normal person (non-technical, non-scientific background) to interpret. Scientists also create language barriers by making their own jargon and writing in ways that are not accessible to most other people and then have problems rewording this information into generally intelligible forms.

In order to break out of this esoteric trap, scientists and any “expert” for that matter need to find an accessible way to explain their work. This is where it becomes necessary to work out what an “explanation” really is (Khalifa, 2013). An explanation should fit the receiver before further dialogue can take place. You can explain a fact at different levels, using different examples and depending on the receiver's background and their capability to understand the message. It also helps the teller who is aided by the simplicity of the message. For example, there is always a difference in explaining how the Earth formed to a 5-year-old versus a 30-year-old, or someone at work versus a holidaymaker. In addition, esoteric scientists often have more difficulty than a broader-based communicator in telling their story, as their message can be clouded in complex jargon.

Similarly, the scientific processes and techniques should be explained on a different basis to a person with a science background and without a science background. Even a scientist who does not have a specific background in a specific subject or technique needs to start in a simple manner. In addition, a specialised scientist can better understand their work with simple explanations that allow them to see around their subject.

If we bridge the gap between the scientific and non-scientific communities, specialists and generalists, it would be much easier to bring scientific works to a larger audience and allow them to contribute to science.

We are starting with a technique whose name itself is challenging for geoscientists, and which is often reduced to an acronym because of its complexity. However, this technique is exceptionally useful and powerful in revealing crucial insights that are valuable for understanding. Thus, we look at ways to introduce and explain the results and techniques of AMS and its application in three different geological sites in a simple and layered way, so that people who visit the geosite and who have no scientific background can understand the scientific explanation for the geosite in addition to its aesthetic beauty.

2. Material and methods

2.1. Study area

Three sites were selected in this study: a highly inaccessible part of Mount Etna (Sicily, Italy), a beach tourist-frequented area of Stromboli Island (Aeolian Islands, Italy), and an area near Saint Nectaire, Massif Central, France, where tourism is mainly related to walking and visits to cheese farms. Specific geosites are the follows:

[1] UNESCO Global Geopark Statutes—https://www.unesco.org/en/iggp/geoparks/council.

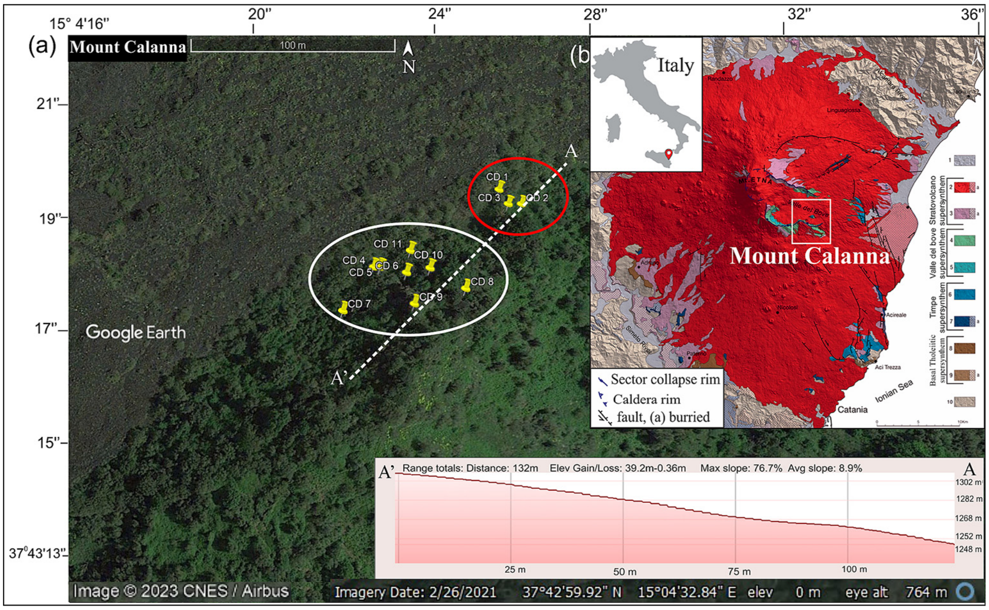


Fig. 1. a. Google Earth image depicting the northeastern part of Mount Calanna with geosites marked. b. Digital elevation model of Mount Etna with the position of Mount Calanna within the context of Italy (left top inset) (modified after Branca et al., 2011).

(1) Mount Calanna dyke swarm of Mount Etna (Italy): despite being a small dyke swarm, it covers an area of about 0.7 km^2 and located southeast of Mount Etna. Mount Calanna is an important geological site to study dyke emplacement mechanisms and the former magma chamber position of Mount Etna (Fig. 1). At the same time, the volcanic evolution of the Monte Calanna within Mount Etna succession is still a discussion among those experts who have been working on Mount Etna (Ferlito & Nicotra, 2010; Ferrari et al., 1989; McGuire, 1982; Nicotra et al., 2011; Romano, 1982; Romano & Guest, 1979; Shajahan et al., 2024). But owing to the poor accessibility and high alteration of country rock and dykes, which mask the original lithology, it is difficult to explore Monte Calanna. The geotourism potential of Monte Calanna is very low/null due to the difficulty of reaching the site, yet we would like to be able to explain why the site is important for the history of Mount Etna to a broad public. Furthermore, as Mount Calanna is being covered by the recent eruption of Mount Etna, it is high time to conduct a thorough study of the area.

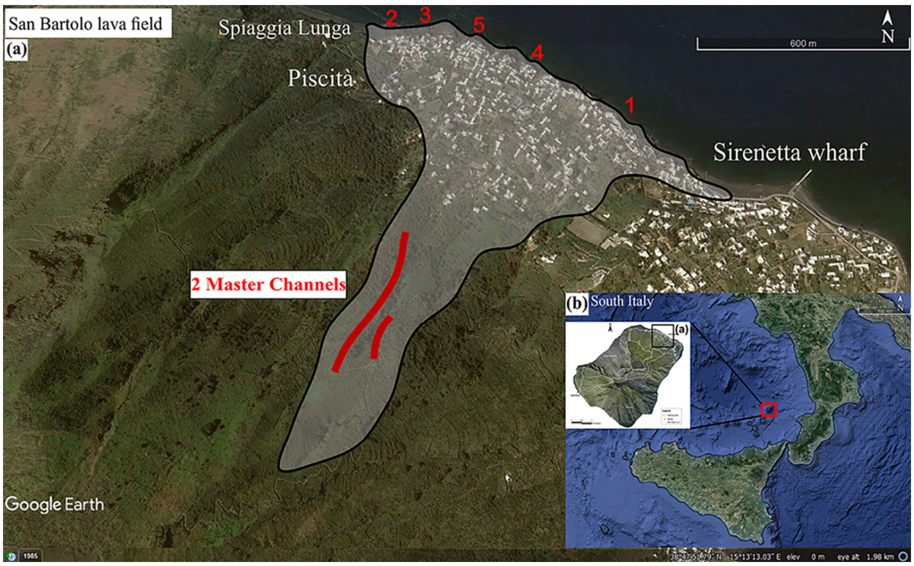


Fig. 2. a. Google Earth image illustrating the lateral extent of the San Bartolo lava flow field in the northeastern part of Stromboli Volcano, with the geosites' locations marked in red (modified after Calvari et al., 2023). b. Google Earth image depicting the position of Stromboli volcano within the context of South Italy. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

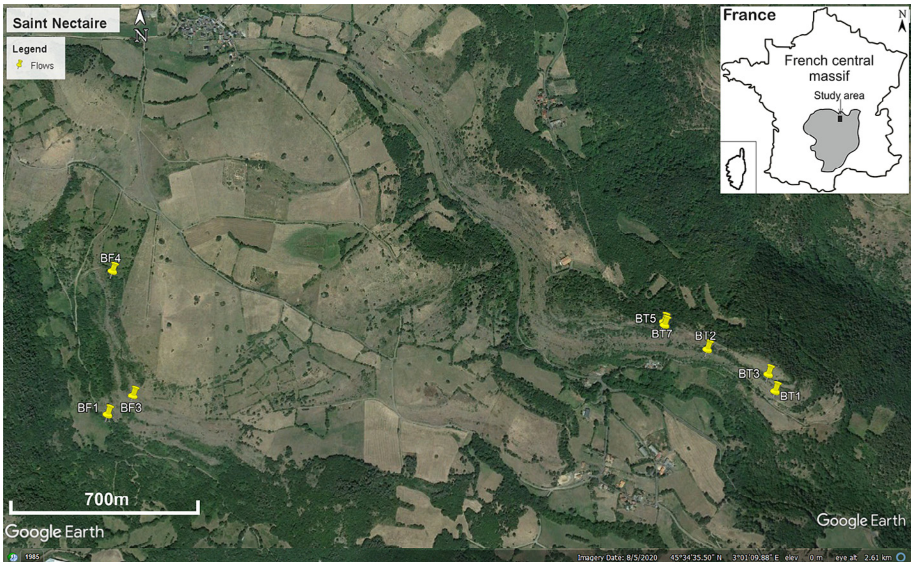


Fig. 3. Google Earth image displaying Thones le Vieux (BT) and Thones le Farges (BF) with the designated geosites marked. The top right inset provides the geosite's location within the context of the French Massif Central.

(2) San Bartolo lava flow of Stromboli (Italy): it is a lava field in the northeast part of Stromboli Island (Fig. 2). The entrainment of lava into the sea and the formation of various lava components make San Bartolo an optimal laboratory for geologists, particularly field volcanologists (Shajahan et al., 2024). In addition, the establishment of one of the island's two townships on the San Bartolo lava field turns it into an important site for locals as well as tourists. More than 70% of the island's tourism surrounds this area. So far, tourists might pass by the lavas without a thought, yet some are also attracted to the rocky coast. Our objective here is to render this coast understandable and thus more interesting and potentially more beautiful. We would like the geoheritage to be preserved not only for the esoteric science but also for a broader understanding of the place.
(3) Thones le Vieux and Thones le Farges of Saint Nectaire, Massif Central of France (Fig. 3): this is a volcanic setting geographically and geologically related to the Massif Central (France). The two different lava successions of Saint Nectaire are located in the eastern distal sectors of the volcanic complex of Mont Dore, about 20 km east of the Puy de Sancy, between the municipal territories of Saint Nectaire and Grandeyrolles. Saint Nectaire has several geological sites of scientific importance as well as tourist appeal.

We used AMS on the igneous rocks of all the geological sites described above for various specific geoscience questions. In doing this, we also built a robust geological field and geoheritage inventory during the fieldwork. The AMS work was added to this, alongside petrological and geochemical information, to make a narrative and explain the AMS results and technique in a simpler way.

We then explored how this could help local people and tourists understand the local geology and the scientific explanation obtained with AMS. Besides giving a scientific background to tourists and connecting people to their local geology, our study could help normal people get a global awareness of the importance of geosite protection, as understanding of a scientific significance can lead to appreciation of an object.

During writing, this process became even more important to us, especially when locals on one site complained about the drill holes, which they felt were damaging the beauty of their rocks. Not only did the holes have to be filled back in and hidden, but their importance had to be communicated. This demonstrated the importance of engaging with locals and providing a clear explanation of the work for them to appreciate. The scientist should always be sensitive to the needs of the local environment—social, cultural and natural—and respect them.

2.2. Methods

The first step in our process is to find ways to make AMS easy to understand. We wanted to test this on "naif" people and experts to see if the message was working. Then, we integrated this into the framework of a geoheritage inventory that was used to choose the best sites for displaying information, which allowed us to pick out the salient aspects to use for clear communication.

2.2.1. Making AMS easy

Making AMS "easy" is *not* easy. It is not simple to explain one of the most advanced and sensitive techniques in rock magnetism. As pointed out in the introduction, it is always important to understand the background of the target public before giving a definition. Accordingly, to target a wide audience, as well as those more knowledgeable, we developed explanations at three different levels—going from highly simple and general to highly specific and technical. This is one of the best approaches we have discovered after discussions with teaching staff and communicators with expertise in general public communication. The levels are listed as follows:

(1) The first level has no need for prior knowledge of magnetism and volcanic settings. Here, we have made a simple and easy-to-understand explanation for anyone, including school students, locals and tourists with no scientific background, and it also works for so-called "educated" people to grasp the simplicity of the concept. This can also be achieved visually, with a simple demonstrative experiment.
(2) The second level relates to knowledge of magnetism, particularly magnetism in rocks. These concepts can be introduced after the first message is received and understood.
(3) The third level uses information and concepts adapted for scientists and any experts who work in different fields or for people who have taken a real interest and developed an understanding through the first steps. Going back to the initial step can always help in understanding the concepts at this detailed level.

The idea of putting simple experimental explanation and visualization before the theory is following the Confucius quote, "I hear and I forget. I see and I remember. I do and I understand." The order is reversed here: first, we do; then, we see the results; and finally, we understand the theory behind it. Even if the latter is forgotten, the other two form a sound base for understanding, and deliver the important basic message.

2.2.2. Understanding the audience

The subsequent step was to understand better the background of the target audience. For this purpose, we prepared a questionnaire with different levels of questions. Our primary targets were locals, tourists, and scientific experts. The questions asked to the natives and tourists were not directly addressing the concept of AMS, but rather to check basic knowledge about the geological environment in which they live or visit and to learn whether they know the scientific explanation for its formation. This part was undertaken as much as possible during informal discussions while conducting fieldwork. Explaining the AMS technique in a simpler way would make more sense to them and could easily relate to what they see. We have done this during field visits to the areas. In addition, among scientists and those from a research background, we circulated a questionnaire to check the concept of AMS and its application. Verbal informed consent was obtained from all subjects before the study.

2.2.3. Making a geoheritage inventory

An inventory allows information to be ordered and structured in a way that makes it useful. In this case, a large amount of observational fieldwork data and AMS data were collected and organized in a structured manner, enabling their use for communicating about AMS. The inventory can also be used for protection, management and other uses. The method we chose for our inventories was the modified geosite assessment model (M-GAM), which facilitated the swift and structured organization of data sets (Jonić, 2018; Tomić & Božić, 2014).

The first step was to use the extensive field descriptions for each area to identify and describe the main geosites. That information was used in each case to give values to each geosite for values, such as the rarity, the representativeness, scientific value (in quantity of published information, and AMS value), as well as educational, touristic, aesthetic and cultural aspects. This information formed the core of the inventory, and its use allowed geosites with good value to be chosen for the next step of integrating the AMS message.

2.2.4. Integrating explanation and inventory results

This final step matched the inventory and the AMS explanations. The first search was carried out to find the geosites that most clearly illustrated the AMS processes and features. The second search focused on identifying geosites that were not only accessible, visible, and safe for the general public but also optimal from a didactic standpoint. Cross-matching the two allowed for a short list of the very best sites to be chosen for communication and provided the background information to be integrated with the explanations. Finally, the explanations should be contextualized for each selected geosite, and communication materials such as posters, guided explanations, information panels, and website content should be prepared accordingly.

3. Results

3.1. Constructing explanations for AMS

3.1.1. First level: Doing

For this first level, we had a simple and practical experiment, which could be performed with any at-hand everyday materials. Formally, it could be enacted by a guide, or could be carried out following a simple set of graphic instructions, on printed format or as a small video.

Basic concept: Things flow down slopes, and anything in it will point the way it's flowing. We initially made a simple and basic experiment, showing honey (it can be another liquid, but honey flows slowly enough to slowly see the changes) flowing down a slope.

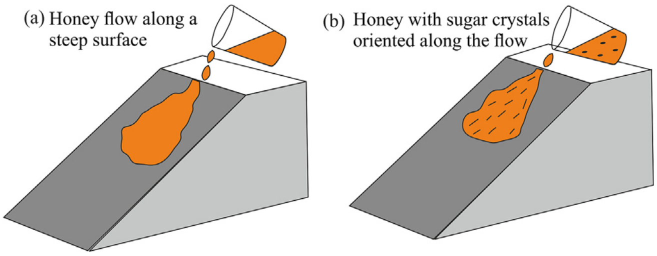


Fig. 4. a. Initial stage of the experiment involving the pouring of honey along a sloped surface. b. Subsequent introduction of sugar crystals into the honey, resulting in crystal flow and orientation along the honey flow. It could even be achieved with water on a rock slab, right in the field.

(1) In a very basic case, pouring the honey, we would ask people to say in which direction the honey is flowing (Fig. 4a). But if you then hide the process of pouring the honey and its flow, and only show the end result, viewers may find it challenging to visualize the direction of flow.
(2) Next, honey with a small amount of sugar is poured, with hundreds and thousands of sprinkles aligned along the flow (Fig. 4b). These are analogous to the magnetic minerals in the lava.

Therefore, the concept of flow markers by crystals was introduced. At this point, a magnet could be shown to indicate that there are little magnetic crystals in a lava. Even if you don't see them, you can measure their magnetic direction and find the flow direction. A compass can be used as a rudimentary magnetometer to show how a magnetic mineral can be detected.

People doing the experiments would now have a simple and practical model in their mind's eye to understand the very basics of AMS. This could help them better understand the flow of the lava or dyke they observed, using AMS. In this way, when anybody who had participated in this experiment would understand the fundamental concept behind AMS when they heard about it. They might think of AMS: "Ah! Flow direction is detected by measuring magnetic minerals." At this stage, the guide could also use images from high-resolution drone flights and immersive reality to help the tourist get a broad picture of the lava flow distribution, which we could measure using the AMS technique (Bonali et al., 2021; Granados-Bolaños et al., 2021).

The same experiment and explanation can also be carried out at the start of level two and level three, as it is always easy to start from a simple "doing" case, regardless of the target group. In these two cases, however, the concept of explanation becomes more in-depth.

3.1.2. Second level: Seeing

In the second level, following the introduction with the basic first level experiment, a scientific interpretation of the process was given. This explanation revolved around the principles of magnetic susceptibility and the magnetic properties of rocks. To begin with, the initial honey experiment was reproduced, but with a slight modification.

Instead of pouring the honey onto a sloping surface, it was poured onto a flat surface. In this context, it was not easy to assess the actual direction of flow until the flow itself was observed. However, the honey was then given bubbles (blown in with a straw, or just made by stirring rigorously). Then the honey was poured again (Fig. 5a). This time, not only can they observe

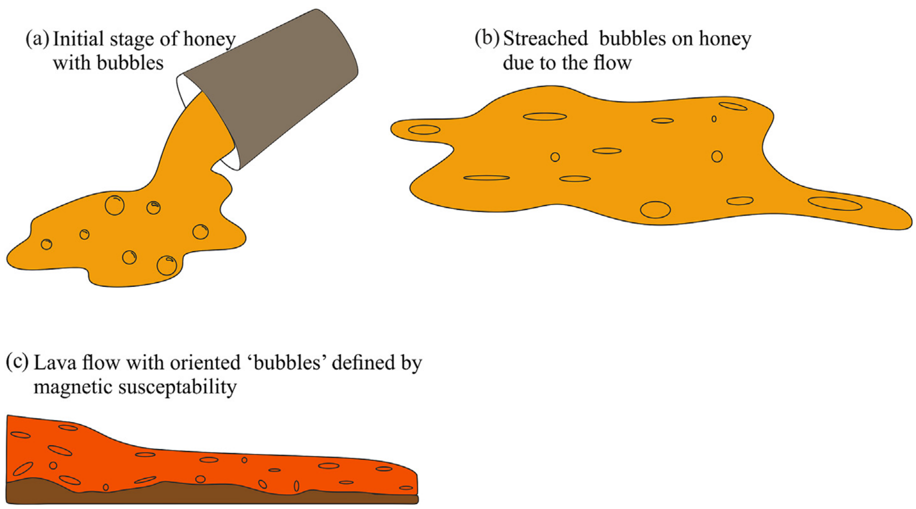


Fig. 5. a. Early stage of the experiment showing the honey being poured onto a flat surface with bubbles. You can see the spherical bubbles as the honey hasn't started to move yet. b. The bubbles in the honey started to stretch and orient themselves as the honey started to flow. c. Schematic diagram showing the distribution of the "magnetic" 3D bubbles in the lava, which is also the orientation of actual bubbles (vesicles, as geologists call them).

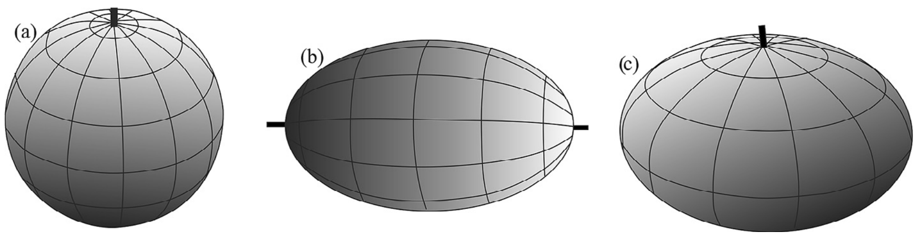


Fig. 6. Schematic representation of sphere (a), prolate (b), and oblate ellipsoid (c). These show whether a lava or magma is undeformed, stretched in one direction, or flattened.

the flow direction, but also they can see the gradual stretching and alignment of bubbles in the flow direction, illustrating the process (Fig. 5b).

Analogous processes occurred within rocks during lava (extrusive surface) and magma (intrusive below deeper) flow. Assuming that each magnetic mineral is an independent bubble, where the "bubble" is defined by the orientation and magnitude of magnetic property, then the orientation of the bubble can indicate the flow direction (Fig. 5c). This magnetic property, which defines the magnitude and direction of the 3D bubble, is called the magnetic susceptibility (K). In other words, it can be explained as a measure of how much (strength) and in which direction (orientation) a magnetic material is magnetised. It is the property of the material, specific to each material. Different crystals have different susceptibilities; iron-rich minerals like magnetite are more susceptible, whereas those with little magnetic material, such as feldspar or quartz, are not. Not only does magnetic susceptibility measure the strength of the response, but also this susceptibility can have a direction of a particular mineral (not to be confused with the magnetic field shown by the compass).

The length, width and height of the "bubble" are indirectly determined by the strength and direction of the magnetic susceptibility. The shape of this "bubble" is not defined by a single magnet, but rather by many tiny magnetic minerals in the rock. Now, the combined strength and general direction of the individual magnetic minerals define the shape. If all the magnetic minerals have the same values for length, width, and height, they give a spherical shape (Fig. 6a). Alternatively, if the height is greater than the width and length, it results in a prolate shape resembling a rugby ball (Fig. 6b). Conversely, if the height is less than the width and length, the shape becomes flattened, like a disc, forming an oblate shape (Fig. 6c).

3.1.3. Third level: Theory

For the third level, we concentrated on a more in-depth, scientific explanation of AMS with some of its applications. As mentioned before, we started with the basic experiment and theory at the initial levels, progressively advancing from simplicity to complexity.

The anisotropy of magnetic susceptibility measurement of a rock gives the results in the form of a triaxial ellipsoid (the virtual "bubble") with the principal susceptibility axes at right angles to each other, $K_{\mathrm{max}} > K_{\mathrm{int}} > K_{\mathrm{min}}$ (K_{max} = maximum susceptibility; K_{int} = intermediate susceptibility; K_{min} = minimum susceptibility) (Fig. 7). K_{max} defines the magnetic lineation and the $K_{max} - K_{int}$ plane defines the magnetic foliation (Fig. 7).

Various quantitative (= scalar = measurable) parameters can be derived from these susceptibility axes to define the AMS ellipsoid, such as the mean susceptibility (K_{mean}), the corrected degree of anisotropy (P_j), the shape parameter (T) and the magnitude of lineation (L) and foliation (F) (Borradaile & Jackson, 2004; Cañón-Tapia & Chávez-Álvarez, 2004; Jelinek, 1981).

K_{mean} gives the arithmetic mean of the principal susceptibility axes, P_j defines the degree of anisotropy and T gives the shape of the AMS ellipsoid, where T can vary from $+1$ (oblate) to -1 (prolate). The distribution of the susceptibility axes on an equal-area projection of the lower hemisphere allows the flow direction to be determined (Figs. 8b and c). The interpretation of the flow direction is not always straightforward, it requires a thorough study of the type of magnetic phase, magnetic domain, post-emplacement process and so on.

Coming back to rocks, in volcanic settings, AMS is mostly used to find the flow direction in a lava and other volcanic processes, such as the emplacement mechanism of dykes. In a lava flow, the ferromagnetic minerals tend to orient themselves parallel to the flow direction (Fig. 8; Cañón-Tapia & Chávez-Álvarez, 2004; Tarling & Hrouda, 1993).

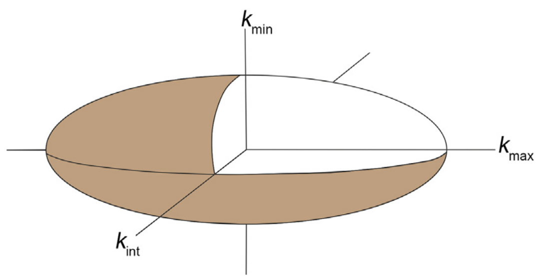


Fig. 7. Ellipsoid of magnetic susceptibility with the principal susceptibility axes.

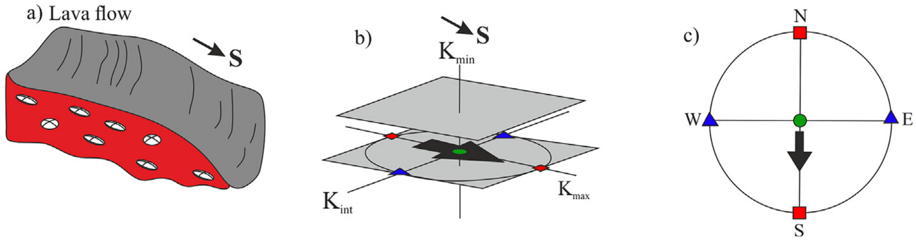


Fig. 8. a. Schematic diagram of south-directed lava flow showing the distribution of susceptibility ellipsoid. b. Stereographic projection of the 3D ellipsoid on a plane. c. Stereographic projection of the 3D ellipsoid on lower hemisphere equal area projection.

A final, most advanced complication is that the interpretation can be complicated by several factors, including the prevalence of different magnetic minerals that hold their magnetism differently. For example, single-domain (SD) magnetic grains cause inverse magnetic fabric (they are magnetised the wrong way round!), making directional interpretation complex (Potter & Stephenson, 1988; Rochette et al., 1999).

3.2. Geoheritage inventory

Following the method outlined above, we created a robust inventory for each geosite by combining all available data. The M-GAM model allowed us to quantitatively assess each geosite and to build a comprehensive framework for each geosite. The proposed inventory contained ten geosites for Mount Calanna, five for San Bartolo, and eight for Saint Nectaire.

3.2.1. Mont Calanna: Dykes swarm of Mount Etna, Italy

Mount Calanna dyke swarm is an isolated hill situated in the southeast of Mount Etna, spanning an area of ~0.7km^2 (Fig. 1). The framework of Mount Calanna comprises numerous basaltic dykes, both altered and unaltered, along with lava flows from ancient eruptive centers that have been completely weathered and eroded (Ferlito & Nicotra, 2010). The altered dykes have a uniform E-W orientation and belong to the Mount Calanna unit, while the unaltered dykes have a random orientation and belong to the more recent eruptive age called Mongibello (60 ka to present) (Ferlito & Nicotra, 2010). The altered dykes are mostly dissected by two sets of mutually perpendicular joints and E-W-oriented normal faults.

Mount Calanna hill is mostly surrounded by lava flows of different epochs, the north and west being covered by lava flows from the latest eruptions, mainly those of 1991–1993 (Fig. 9). The east is covered by the porphyritic lava flow from the recent dykes that erupted across Mount Calanna. Absolute dating of the Mount Calanna dykes is not feasible due to their high alteration. However, $^{40}Ar/^{39}Ar$ dating of a rock from Val Calanna, located south of Calanna hill, yielded an age of 128.7 $\pm$ 3.8 million years (Branca et al., 2008).

This small dyke swarm of Mount Calanna gained considerable interest among geologists when Ferrari et al. (1989) presented Mount Calanna as evidence for the gravitational spreading of Etna's eastern flank due to the presence of several thrust faults. A later study by Ferlito and Nicotra (2010) contradicts this statement, as they did not find evidence of faulting but instead interpreted Mount Calanna as being under a N-S extensional regime. The unresolved question of the volcanic succession of Mount Calanna is another factor that makes this dyke interesting for researchers, given its importance in the evolution of Mount Etna (Ferlito & Nicotra, 2010; Ferrari et al., 1989; McGuire, 1982; Romano, 1982; Romano & Guest, 1979). Apart from the steep slopes and the dense vegetation that impedes access, the dykes are being covered by recent lava flows and ash falls. The study by Ferlito and Nicotra (2010) reported the presence of more than 200 dykes on this small hill, with an intrusion intensity of up to 40%. However, the recent fieldwork carried out by us confirms that more than 90% of the dykes are under vegetation and covered by ash fall (Shajahan et al., 2024).

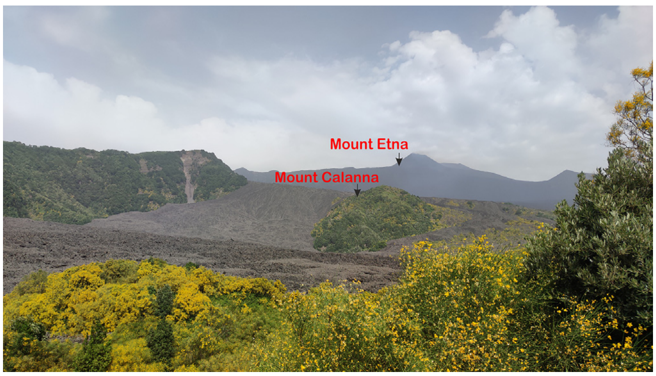
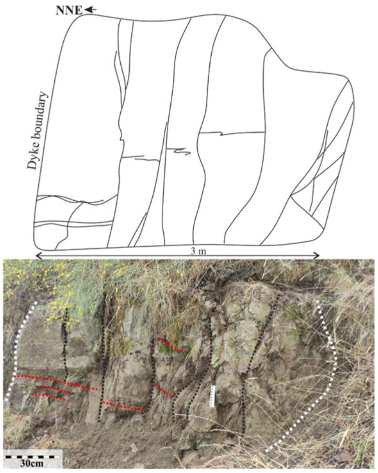
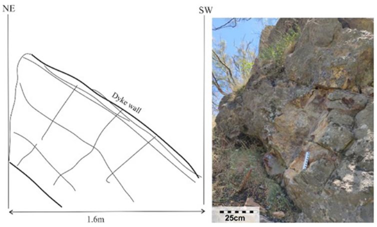


Fig. 9. Field photo of Mount Calanna, which is surrounded by recent lava flow and covered by high vegetation.

Table 1
Short description of two representative geosites (dykes) from Mount Calanna with their field photos and sketches.

Name	Description	Field Photo
CD1	It is one of the newly-formed dykes, emplaced sub-vertically, measures 3 m thick and is oriented E-W, making it easily accessible and visible. It is deselected by two sets of joints, sub-vertical joints oriented NW-SE and sub-horizontal joints oriented NE-SW. Magnetic fabric shows sub-vertical flow striking towards SW.	
CD2	It is an altered dyke, emplaced sub-horizontally, with a thickness of 1.6 m. It has the local presence of pyroxene phenocryst and vesicles at the dyke centre. Two sets of joints (sub-vertical and sub-horizontal) dissected the dyke into small blocks. The dyke is quite visible, with less vegetation around. So, it is comparatively more accessible. Magnetic fabric shows sub-horizontal flow striking NW-SE.	

We made an inventory of Mount Calanna dykes using the available data and assessed the potential of the geosite (dyke) using M-GAM. The list of two representative geosites with their main characteristics is given in Table 1, and the rest is compiled in Table A1 in Appendix. Following the standard procedure of M-GAM, we compiled the data from experts and tourists—Importance Factor (Im)—to generate the final ranking of the dykes of Mount Calanna using the M-GAM matrix (Table 2 and Fig. 10). Given that Mount Calanna is not a tourist destination and lacks proper access paths, we collected the opinions of 15 individuals who have previously visited the site to calculate the Im.

For the geosites in Mount Calanna, the highest-rated sub-indicators were representativeness (0.90), environmental fitting of sites (0.90), current condition (0.90) and interpretative panels (0.95) (Table B1 in Appendix). It was interesting to note that, apart from knowledge of geoscientific issues, all other sub-indicators of scientific/educational values were deemed important for tourists. People visited Mount Calanna mainly for trekking, where they expected to be closer to nature and have the trekking experience. For this reason, the important road network (0.25), restaurants (0.20) and the additional functional values (0.35) such as toilets and rest areas were not so important to them Table B1 in Appendix.

As all the dikes have mostly the same characteristics, the results obtained showed almost the same value for the main values and the addition values of all ten geosites. The geosites CD1 and CD2 showed a slightly higher rating for the main value, specifically 3.14 and 3.20, respectively, compared to the other geosites (Table 2). This was due to the high value of the two sub-indicators: representatives and knowledge on geoscientific issues. The mean average of the additional values for all ten geosites had the same low value (2.16) as all the sub-indicators were rated low (Table 2). The geosites of Mount Calanna had been plotted on the M-GAM matrix (Fig. 10) with means of the final value of the main values and additional values. As expected, all ten geosites fell within the area of Z_{11}, with low final scores for main values as well as additional values.

Table 2
Final ranking of the Mount Calanna dykes by M-GAM.

Geosites	CD1	CD2	CD3	CD4	CD5	CD6	CD7	CD8	CD9	CD10
Main values	3.14	3.20	2.53	2.98	2.91	2.75	2.75	2.69	2.75	2.69
Additional values	2.16	2.16	2.16	2.16	2.16	2.16	2.16	2.16	2.16	2.16
Fields	Z_{11}	Z_{11}	Z_{11}	Z_{11}	Z_{11}	Z_{11}	Z_{11}	Z_{11}	Z_{11}	Z_{11}

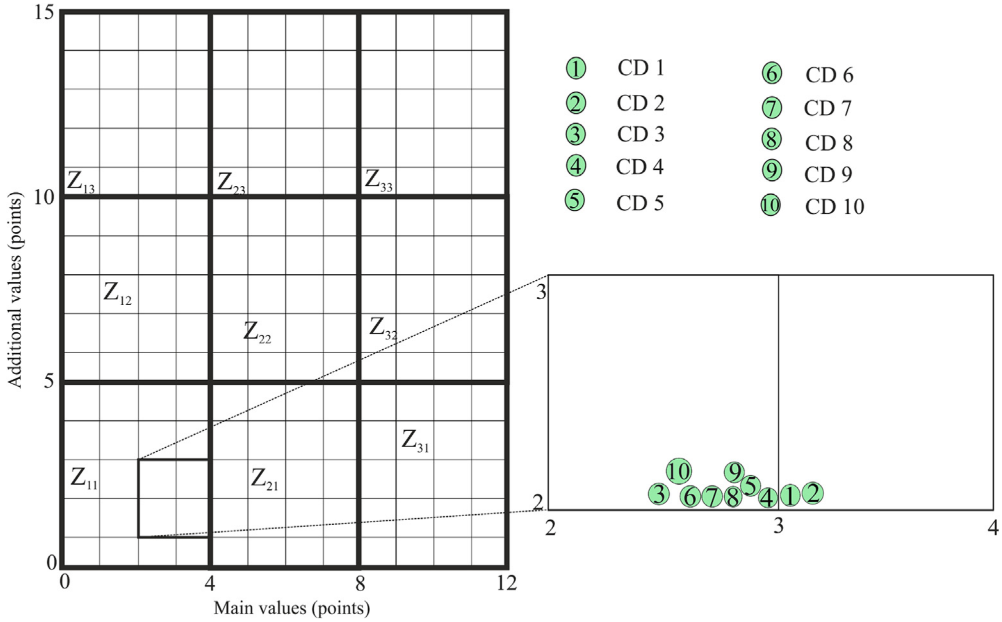


Fig. 10. Distribution of the geosites of Mount Calanna in the M-GAM matrix.

3.2.2. San Bartolo lava flow of Stromboli, Italy

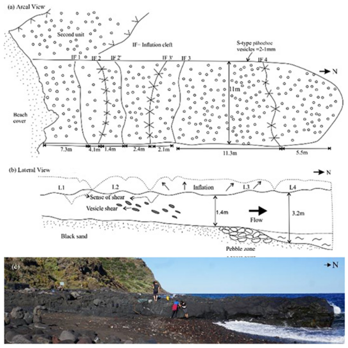
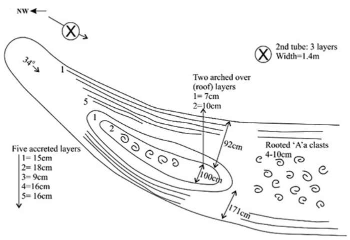
Stromboli is one of the most active volcanic islands of the Aeolian archipelago, situated in the southeast of Italy (Fig. 2). The beautifully exposed lava along the coastal line and the low-energy volcanic eruptions attracts people worldwide. More than half of the total settlements are on a recent lava flow called San Bartolo, which has an age of ~2 ka (Arrighi et al., 2004; Speranza et al., 2008) and emplaced on the northeast of Stromboli. The lower part of the San Bartolo lava flow forms a delta and is characterized by the formation of several semi-arcuate structures, referred to here as, at the flow front due to the interaction with the sea (Calvari et al., 2023). While San Bartolo is a site of interest to the scientific community because of the lava-sea interaction, it is also a well-liked tourist attraction because of its beautifully well-exposed beaches and surrounding landscape. The whole flow field of San Bartolo lava comprises 15 different flows, which fan out as a lobe formed by the interaction of lava with water. These flows are characterized by the presence of different lava components, mainly tube, inflated pāhoehoe, littoral, channel and ramp components (Shajahan et al., 2024) (Table A2 in Appendix). Here, we defined each component as an individual geosite in order to explore the geotourism potential and provide an improved management plan for geotourism. Two representative geosites with their corresponding descriptions and field photos are summarized in Table 3.

In order to assess the geoheritage importance and geotourism potential of the beach at the flow front of the San Bartolo lava flow, we quantified the importance of the various exposed components using M-GAM. The final M-GAM results with the aggregate of main values and additional values for each geosite are given in Table 2 and Table B2 in Appendix. According to the tourist's evaluation of the importance of each sub-indicator (Im), scenic or aesthetic values were of high importance compared to scientific and protection values (Table B2 in Appendix). It may be that tourists who visit a volcanic island for a beach holiday are mostly among the “general” geotourists (Božić & Tomić, 2015). Thus, they are more interested in the aesthetic value of the geosite rather than its scientific importance. In addition, tourists tend to pay little heed to additional amenities like road networks, parking facilities, and gas stations, as they normally do not anticipate or concern themselves with such conveniences when visiting an island.

The sea entry of lava and the small beaches with caves formed by the erosion of the levee make the San Bartolo interesting to visitors from an aesthetic and bathing point of view. At the same time, the well-developed and preserved morphology of the lava and the different volcanic components due to lava-water interaction make it highly interesting to volcanologists (Calvari et al., 2023). Looking at the final M-GAM results, it was clear that there was no apparent difference in the total main and additional values between the individual geosites (Table 4). However, due to the lower representativeness and chaotic nature, littoral components had a slightly lower main values (4.51). In terms of main values, all the geosites showed higher values due to the higher values for representativeness and knowledge of geoscientific issues.

From the M-GAM matrix shown in Fig. 11, we can see that all the five geosites were in the middle field (Z_{22}) for both main values and additional values. This clearly showed that it had the potential to attract both “general” and “pure” geo-tourists (Božić & Tomić, 2015). As all the sites were closely grouped, the inventory did not single out sites for the communication of AMS, these had to be chosen in relation to the best positioning for information.

Table 3
Short description of the proposed geosites of San Bartolo lava flow with the field photos and sketch.

Name	Description	Field Photo
Inflated pāhoehoe	It is the classic example of inflated pāhoehoe lava component at Flow 12, which is at the southwest end of the San Bartolo flow unit. The upper brittle surface crust, the massive core, and a small viscoelastic layer between them are clearly visible. The brittle crust was characterized by the vesiculated s-type pāhoehoe lava, while the central core has a massive, less vesiculated lava. At the surface, there are four inflated lobes, which are separated by the inflation cleft. As this geosite is at one of the main beaches in Stromboli, Spiaggia Lunga, it can be easily reachable and is well visible. Moreover, tourists mostly lounge on the spacious surface of the inflated pāhoehoe units. The process of inflation of the upper thin brittle layer is obtained from the vertical magnetic foliation plane, whereas the horizontal lava flow of the lower part is obtained from the sub-horizontal magnetic foliation plane.	
Tube component	There are two tubes at Flow 1, which extends NE. The top of the tube got eroded by wave action, so the internal structure is visible and is quite well preserved. The main tube has five accretionary layers and two arched-over layers. The central stream has rooted ‘A’a clasts. This geosite is a good example to study the characteristic features and the formation of tube component. As the tube outcropped at the beach, it is easy to reach the geosite and is risk-free to visit and explore the site. The AMS results indicate a vertical foliation plane with flow towards south.	 

3.2.3. Thones le Vieux and Thones le Farges lava flow of Saint Nectaire

The two lava flows, Thones le Vieux and Thones le Farges, in Saint Nectaire are part of the Mont Dore-Sancy volcanic complex, which is geologically and geographically linked to the Massif Central, a vast mountainous and hilly area of central-southern France (Fig. 3). The Mont Dore-Sancy complex is a composite volcanic edifice covering an area of ~500 km^2 for a volume of material produced of approximately 200 km^3 (Brousse, 1971; Vincent, 1980).

The two main lava successions, a few kilometres apart, known as the Thones le Vieux and Farges series, are located in the eastern distal sectors of the Mont Dore volcanic complex. Besson (1978) dated these lavas to about 3.8 Ma from a stratigraphic comparison with lavas from the Puy de Bessoles. Lesage (2013) suggested a different origin and flow for the Thones le Vieux and Farges series and emphasised that it was not possible to witness reliable correlations between the successions. Geochemical studies show a strong alteration in some units of the lava sequences, particularly those at the base. However, the morphological and structural elements derived from the soil analysis of the outcrops do not suggest any relationship between the two.

The complete succession of Thones le Vieux consists of seven units (BTn), with a total thickness of ~90 m and a maximum elevation of 835 m a.s.l. The sequence constitutes an inverted relief, elongated in a WNW-ESE direction near the village of Thones le Vieux. Farge series consist of five units (BFn). The outcrops are located southeast of the village of Farges, along the southwestern escarpment of the Lacha plateau, on the road connecting the village of Farges with that of Thones le Vieux. The succession shows a thickness of about 90-100 m and culminates at about 876 m a.s.l., 1200-1500 m from the series at Thones le Vieux.

In our study, we evaluated eight different lava sequences, five from Thones le Vieux (BT1, BT2, BT4, BT5 and BT7) and three from Thones le Farges (BF1, BF3 and BF4) of Saint Nectaire, based on their outcropping (Table 5). In order to obtain the opinion of visitors regarding the importance of each sub-indicator (Im), we conducted 15 surveys with groups of five people who discussed the site together (Table B3 in Appendix). According to them, the important sub-indicators were representatives (0.83), level of interpretation (0.90), viewpoints (0.90), surrounding landscape (0.91), and accessibility (0.92).

Table 4
Final ranking for the geosites from San Bartolo lava flow by M-GAM.

Geosites	Lava tube (SB1)	Inflate pahoehoe (SB2)	Littoral component (SB3)	Ramp component (SB4)	Channel-levee (SB5)
Main values	5.31	6.20	4.51	5.61	6.03
Additional values	6.23	6.64	6.29	6.13	6.44
Fields	Z_{22}	Z_{22}	Z_{22}	Z_{11}	Z_{22}

Visitors to the area were mostly local people who come for walks or short treks, along with geology students who constituted a significant portion of each surveyed group; the remainder comprised non-geologist scientists. For them, therefore, the scenic or aesthetic value was more important than protection. Moreover, people who came to spend their leisure time did not pay much attention to the knowledge of geoscientific issues (0.38). It is also interesting that viewpoints, surrounding landscape and level of interpretation had high values (>0.80), which was not expected in this case, but probably correlated with the geological viewpoint of the public surveyed. For the visitors in Saint Nectaire, the least interested sub-indicators were the annual number of organized visits (0.12) and additional anthropogenic values (0.15).

Among the described geosites in Saint Nectaire, BT1 (4.25) and BT4 (4.32) got the highest main values (Table 6 and Fig. 12). This was because of the high value of representativeness and viewpoints. Whereas BT5 (3.00) and BF4 (3.09) had the lowest main values due to the absence of viewpoints and poor representativeness. Looking at the additional values, BT1 had the highest value (3.13) owing to its highest value for accessibility (1.00) as compared to the rest of the geosites (Table 6). It was interesting to note that, though BT4 had the highest main value, it was one of the geosites with the lower additional value. This was mainly due to the lower value for functional values, especially accessibility.

Compared to the main values, the additional values show more differences among each geosite, mainly because of their different representativeness, level of interpretation and aesthetic values. This places the geosites in two different fields in the M-GAM matrix, with BT1 and BT3 falling in field Z21 and the remaining geosites in the Z11 field (Fig. 12).

As the geosites have values that are grouped, so each one could serve as a site for AMS communication. However, a few geosites stand slightly apart for main or for additional values. And these, BT1 and BT4, as well as BF1, would be the best candidates to develop.

4. Discussion

Considering first the inventory results, we discussed which sites and areas stood out for possible use in delivering the AMS message. For each geosite, a recommended way of presenting the results was given. It logically involves further investigation on these sites, as well as testing on others. This could include employing various scientific techniques that require further understanding, such as age dating, petrological analysis, geochemistry, and the interactions between biology and geology.

To ensure a fair assessment of the importance of each sub-indicator while mitigating potential biases introduced by tourist and other respondent preferences, we made a deliberate effort to encompass both “general” and “pure” geotourists. The obtained data on the importance value given by the tourists in three different geological sites showed that the importance of each sub-indicator of M-GAM was entirely specific to each geological site. This also allowed us to classify the geotourists at these three geological

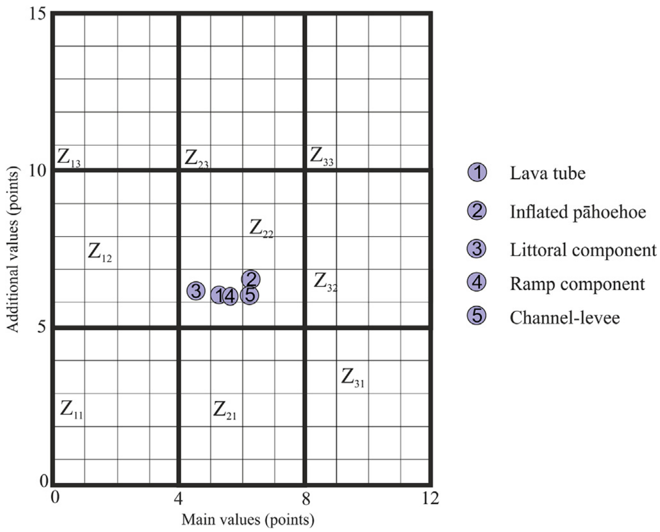


Fig. 11. Distribution of the geosites of San Bartolo lava flow in the M-GAM matrix.

Table 5
Short description of the proposed geosite of Thones le Vieux and Farges lava sequences with the field photos.

Name	Description	Field Photo
BT4	The components are columnar of a thickness of 5 m and at an elevation of 778 m a.s.l., with the lavas being more vesicular than the previous ones. The columnar joints are strongly altered. The base of the wall has a centimetric layer of breccias mixed with small portions of terrigenous sediments, and the upper part of it has rounded quartz fragments marking a sedimentary detrital level. The well-developed magnetic foliation plane shows a subvertical lava flow. A clear trail starting from the bottom of the lava unit takes you to BT4, as it is exposed at the top of the plateau. This geosite can be accessed by walking along the trail and is completely safe. In addition, the magnificent view of the entire Saint Nectaire village makes this geosite more attractive to tourists.	
BF1	BF1 is highly altered outcrop at the base of the Farges series. This flow is lying above the granitic basement and Oligocene sediments, which are not visible because they are covered by vegetation and colluvium. The lavas present onion alteration structures at the base, followed by small columnar joints. Interestingly, at the base of the Farges series, we found a highly altered layer with hydrothermal alteration, which confirms the lower sequence of BF1. AMS results gave a sub-horizontal lava flow direction with the flow striking along NW-SE.	

sites according to the classification of Božić and Tomić (2015). Visitors to Mount Calanna fell into the category of pure geotourists. The only people who visited the geosites of Mount Calanna were geologists or naive tourists (mainly adventurous trekkers) who visited for personal experience and education, mainly in the context of Mount Etna.

At the San Bartolo geosite, the main purpose of the visit was relaxation and recreation, i.e., general tourism. Incorporating scientific information presented an opportunity to appeal to both pure and general geotourists, thereby promoting geotourism.

Given that the majority of visitors to the geosites of Thones le Vieux and Thones le Farges were geologists conducting research, students, and local residents, the visitor demographic at these sites encompassed a combination of both “general” and “pure” geotourists. It was worth noting that, aside from the two categories mentioned above, visitors to San Nectaire included individuals from nearby villages who engaged in leisurely Sunday walks. These individuals were the most frequent visitors to these geological sites.

The M-GAM matrix showed that the geosites from the three geological sites formed three independent clusters (Fig. 13). The San Bartolo geosites had medium main values and additional values. Although the San Bartolo geosites had high scientific value in terms of their representativeness and contributions to geological knowledge, there was a clear lack of enhancement in additional values. However, the geosites could be strong contenders for geotourism potential due to their scientific and touristic interests. This was because the entire San Bartolo lava flow field offered compelling settings to study ‘A’ā lava interactions with the sea and showed the intricate dynamics of lava-water interactions. Along the San Bartolo coastline, prominent volcanic features, including ramps, lava tubes, and inflated lobes, were well-exposed, offering a valuable resource for volcanologists to learn and study. Additionally, Stromboli Island was renowned for its tourism, particularly its beaches and volcanic trekking opportunities. Over 70% of the island's population and settlements were concentrated in the northeastern part, in particular above the San Bartolo lava flow field. This highlighted the considerable potential for geotourism and geoscience education at the San Bartolo geosites. The M-GAM suggested that improving geotourism presence and experience could be achieved by increasing additional values, promoting geotourism (such as training guides and leaflets for tourist offices/hotels), enhancing tourism infrastructure (including signage and access path improvements), and introducing interpretative support with simple, attractive graphics, and QR codes for visitors to access information (Quesada-Valverde & Quesada-Román, 2023). This approach would attract people to the area with the expectation of finding something of interest, enabling them to appreciate the rocks not just as a backdrop but as subjects of geological fascination. It would guide them towards areas of geological interest and facilitate their initial understanding of the AMS.

The geosites at Mount Calanna were characterized by relatively low main and additional values (Fig. 13), as expected by its remoteness, primarily caused by challenging access and poorly defined paths. In addition, Mount Calanna was mostly surrounded by recent lava flows and covered by dense vegetation and volcanic ash fall, obscuring our target geoheritage features. These constraints also prevented geologists from studying the emplacement dynamics of this small dyke swarm, which was nevertheless an important part of Etna's evolution. The MAGM analysis showed that this area was not appropriate for communicating AMS, as it was hard to see how any of the values could be raised easily. The only way would be to have some remote/virtual information. But due to the isolation and the paucity of visitors, even this may not be viable.

Table 6
Final ranking for the Thones le Vieux and Thones le Farges geosites using M-GAM.

Geosites	BT1	BT2	BT4	BT5	BT7	BF1	BF3	BF4
Main Value	4.25	3.45	4.32	3.00	3.85	3.43	3.37	3.09
Additional Value	3.13	2.67	2.44	2.44	2.67	2.90	2.44	2.67
Field	Z_{21}	Z_{11}	Z_{21}	Z_{11}	Z_{11}	Z_{11}	Z_{11}	Z_{11}

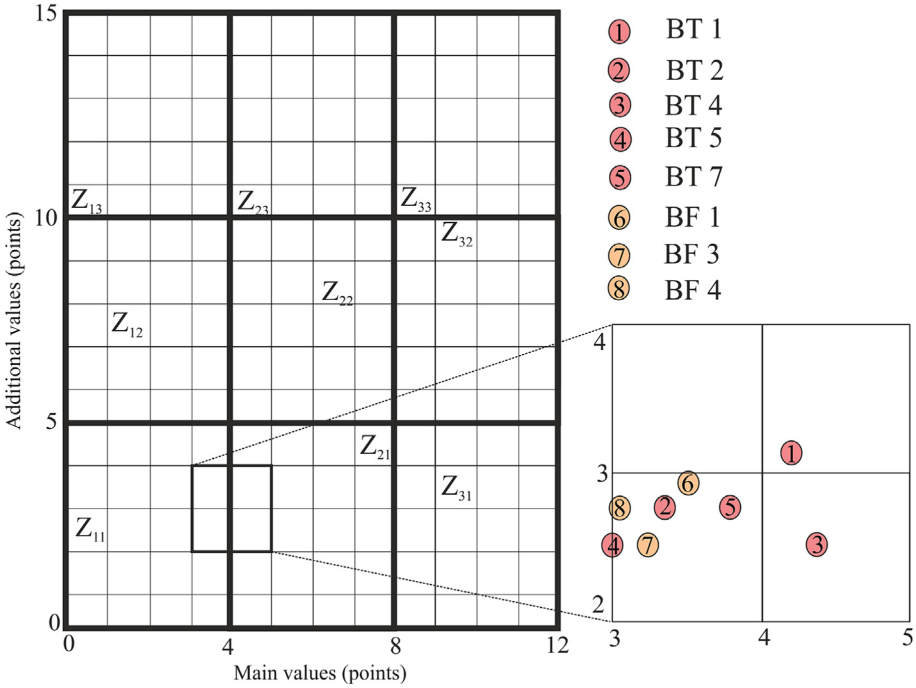


Fig. 12. Distribution of proposed geosites from the lava flow of Saint Nectaire in M-GAM matrix.

The Thones le Vieux and Thones le Farges geosites exhibited a relatively low to medium main values and low additional values (Fig. 13). Given this, there was potential to increase their main values by enhancing their scientific and protection values. The remarkable viewpoints and the surrounding landscape already had a strong appeal; therefore, by enhancing the scientific attributes, we could not only foster a deeper appreciation among normal tourists but also attract geotourists to these sites. In essence, some of this work is already underway with ongoing research in the area, which is expected to increase the main values as more scientific elements come to light.

The main reason for the relatively low rating of additional value was the insufficient touristic infrastructure at these geosites. The absence of properly maintained trails, interpretive panels and geotourism promotion initiatives significantly detracted from the overall visitor experience. These three factors are crucial for boosting the attractiveness of these geosites to current and

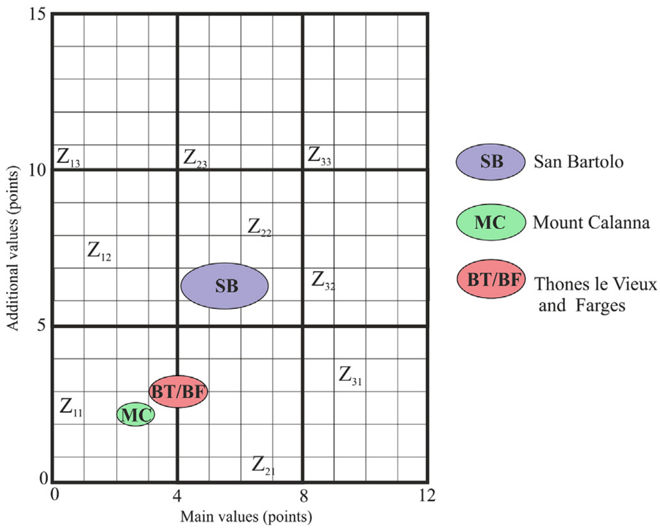


Fig. 13. Distribution of the averaged position of the defined geosites of Mount Calanna (MC), San Bartolo lava flow (SB) and Thones le Vieux and Thones le Farges lava flows (BT/BF). With more scientific knowledge, the main values of each site could increase. However, for Mount Calanna, its main values are already established and could be diminished by natural destruction from Etna lava flows. Additional values for San Bartolo could be enhanced by providing more tourist information at local information points, which could also improve communication for AMS. As for the French sites, a more comprehensive information and amenity package might be necessary, but there is ample opportunity for this improvement.

prospective tourists. Addressing these issues would not only increase value, but also create a more enriching and informative environment for all visitors.

It is worth considering with whom such work could be conducted. At present, the locals—residing in a nearby small village and some farms—are not involved in any tourism activities.

There is one place for tourist accommodation in the small village of Thones, which has views over the area, and may have an interest in increasing its offer to visitors. Otherwise, other nearby sites, such as the Mystères de Farges[2] a few km away, which cater to tourist visits, may provide some support for further extension. These are elements to work on in a future project, if Thones would be developed as a geotouristic site.

Recognising the significant geotourism potential associated with the San Bartolo lava flow on Stromboli volcano, we took the strategic decision to use this site to integrate the AMS explanation with the geoheritage inventory. Given people's strong interest in volcanism and its geomorphology (Németh et al., 2017; Quesada-Román & Pérez-Umaña, 2020; Quesada-Román et al., 2021), our primary goals are to enhance the visitor experience by disseminating knowledge about lava flow dynamics and emplacement processes. Additionally, we aim to introduce the concept of AMS gently, using accessible means linked to everyday experiences.

As a first step, for this article, we decided to create an informative interpretive panel near the coast of San Bartolo, which could also feature in a tourist leaflet. This displays features with compelling graphics, which efficiently provide the main geological insights from AMS analysis (Fig. 14). The objective is to engage and educate visitors, enabling them to access and appreciate geological information more readily. By utilizing visual representations, these insights become more accessible and engaging (Fig. 14). They can then lead visitors to the three-level AMS explanation. This information can be placed on a website accessible via QR code and delivered by local guides and tourist actors, who can be trained to present it in their own style.

During our fieldwork at the San Bartolo lava flow, we observed a notable interest among tourists for gaining a deeper understanding of the lava flow process and our ongoing scientific endeavours. Visitors frequently approached us with curiosity, seeking information about our work. Thus, the introduction of interpretative panels (at least accessible via a QR code) would not only provide valuable insights to inquisitive tourists but also serve as a medium for them to enrich their experience and knowledge during their visit (Fig. 15). Using the medium of AMS, we conveyed the necessary information to visitors in simple and understandable language.

Visitors interested in knowing more about the site can scan the QR code on the panel. This will direct them to a user-friendly platform featuring a three-level explanation of AMS. Additionally, they will discover the emplacement model derived from our AMS study (Fig. 15). This method of presentation facilitates the promotion of geotourism and the dissemination of scientific knowledge to the general public by showcasing comparable geological discoveries from different geosites. It takes a simple explanation of AMS, embedded in accessible, tourist-friendly material, to pique their natural curiosity and draw them in. Alternatively, the visitors may be informed and guided by local tourist actors. Moreover, if scientists are present and working on-site, they now have a platform and method to explain their work as well.

The method we have developed and used has shown that this approach could be effective in bridging the gap between the scientific and non-scientific parts of society. It not only allows the public to see how the message is received but also fosters the creation of new projects, enhancing understanding between scientists and the public. The AMS technique has been widely used in volcanology for more than five decades, the methodology we have developed here can be applied to other volcanoes and geological sites, especially those of high tourist interest, where the AMS results can be easily presented. An example like Pompeii in Italy, which was destroyed and preserved by the AD79 Vesuvius eruption, demonstrates how AMS studies can be clearly explained to tourists (Gurioli et al., 2005; Zanella et al., 2007), using the methodology proposed here. Moreover, the same techniques can be used with other volcanic geoheritage site studies, including those from volcanoes in Costa Rica (Quesada-Román & Pérez-Umaña, 2020; Quesada-Román et al., 2021), Chaîne des Puys, Auvergne in France (Loock et al., 2008; Petronis et al., 2013; Petronis et al., 2019), Canary Island volcanoes in Spain (Dóniz-Páez et al., 2020), or Xitle volcano in Mexico City (Guilbaud, Ortega-Larrocea, Cram, & van Wyk de Vries, 2021).

The system diagram in Fig. 16 shows the full process that we have enacted and indicates a generalized method to undertake the exercise with other scientific information. We suggest that it can be used for any type of communication, such as panel design, websites and social media.

In our tests on "naif" audiences and other scientists, there has been a general acknowledgement that this approach has helped in understanding AMS. It remains to implement the technique in the field and test it with tourists and local actors around San Bartolo, which should be the next step.

The process described here (Fig. 16) depends on putting the scientists within society, allowing them to interact in a more open way. Either part may initiate the initial dialogue, but it can happen only if there is close proximity and ease of interchange. At each step of the process, the researcher and their interlocutors improve their communication and enhance their capacity or potential for understanding. The "Consultation" space is where this occurs and can lead to the joint definition of a subject for research and explanation. This approach not only facilitates explanations derived from scientific work but also ensures ongoing interaction through the consultation process. The choice of sites is a combination of the consultation (part of the participatory geoheritage inventory, M-GAM in this case) with scientific work, forming a cycle involving explanation, inventory, and assessment. The outcome can be both the popular descriptions and arcane scientific work. These are given a voice through the simplification process and improved communication. There is then a feedback loop to society, including the scientist, and further consultation.

[2] https://www.st-nectaire.com/mysteres-de-farges/.

Fig. 14. Cartoon illustration of the use of the AMS technique to find lava flow direction. This uses an anthropomorphised horse-shoe magnet "Maggie magnet" and a cartoon lava with bar magnets. This is the printed version of the simple first-level experiment.

The positive cycle of understanding can begin at various stages. While starting with consultation would be ideal, existing scientific work (often the case) can also provide an explanation that can be enhanced through consultation. For another example, where a site exists with some reality (like tourist visitation or cultural significance), the process can begin from this point, seeking explanations and scientific material to initiate a consultation process.

An important point to add is the use of the M-GAM method in assessing the geosites. While M-GAM is highly effective for the expert, its complexity may be a challenge for the general public. To encourage wider public participation, a more accessible and open form of assessment is recommended. By simplifying the method to include simple questions and allowing room for general comments, a broader audience can contribute their perspectives on the importance of these sites. This inclusive approach promotes a collaborative effort to understand and conserve geosites, ensuring that the insights of both experts and the general public are considered in the management and conservation of these valuable geological landmarks. This observation underscores the significance of this study, emphasizing the need for inclusive approaches in science that can involve a wider range of the public.

5. Conclusions

Scientific studies, with their methods and findings, often pose significant challenges for non-specialists due to their esoteric and arcane nature. This can result in a lack of societal appreciation for the science and hinder mutual understanding between scientists and the community or visitors. To change this poor situation, the primary challenge is thus to effectively communicate and clarify the scientific techniques utilized in research to the general public in a simple and understandable way.

We have chosen AMS as an excellent test case of an inaccessible technique, far removed from normal experience. Initially, we explored how to make AMS understandable, starting by looking at how to communicate the technique in a clear and simple way, with a layering of increasing complexity. To evaluate the efficacy of the AMS explanation, we opted to examine three distinct volcanic sites.

To identify the most suitable candidate for potential applications, we deemed it essential to conduct a geoheritage inventory for each site, utilizing the M-GAM method for this purpose. Our assessment involved a combination of our own understanding of the sites and solicited external viewpoints, wherever feasible.

Utilizing the M-GAM results, we focused on identifying suitable areas for AMS communication, and the best geological sites. Consequently, geosites from Mount Calanna were excluded due to their limited potential for effective communication, as indicated by the low M-GAM values that could not be enhanced. In contrast, geosites from Saint Nectaire showed promise, with the potential, and opportunity for both main values and addition values to increase. Although it currently lacks sufficient visitation to be financially viable, there is optimism that as the scientific significance of the main values grows through ongoing research, local tourism stakeholders may become increasingly interested in its promotion.

The geosites of the San Bartolo lava flow on Stromboli Island have emerged as the most promising, possessing the highest primary and ancillary values, and showing the greatest potential for enhancing geotourism. M-GAM analysis reveals well-defined sites within this area, providing optimal and straightforward opportunities for effective communication.

With our focus set on San Bartolo, we coupled all the tangible geological features of outcrops with intangible elements (rock magnetic data) and built a narrative for popular comprehension of AMS, in the context of the local geology of lava flows. The subsequent phase involved collaborating with tourism and other actors on Stromboli to spread the message, install information panels and employ other media.

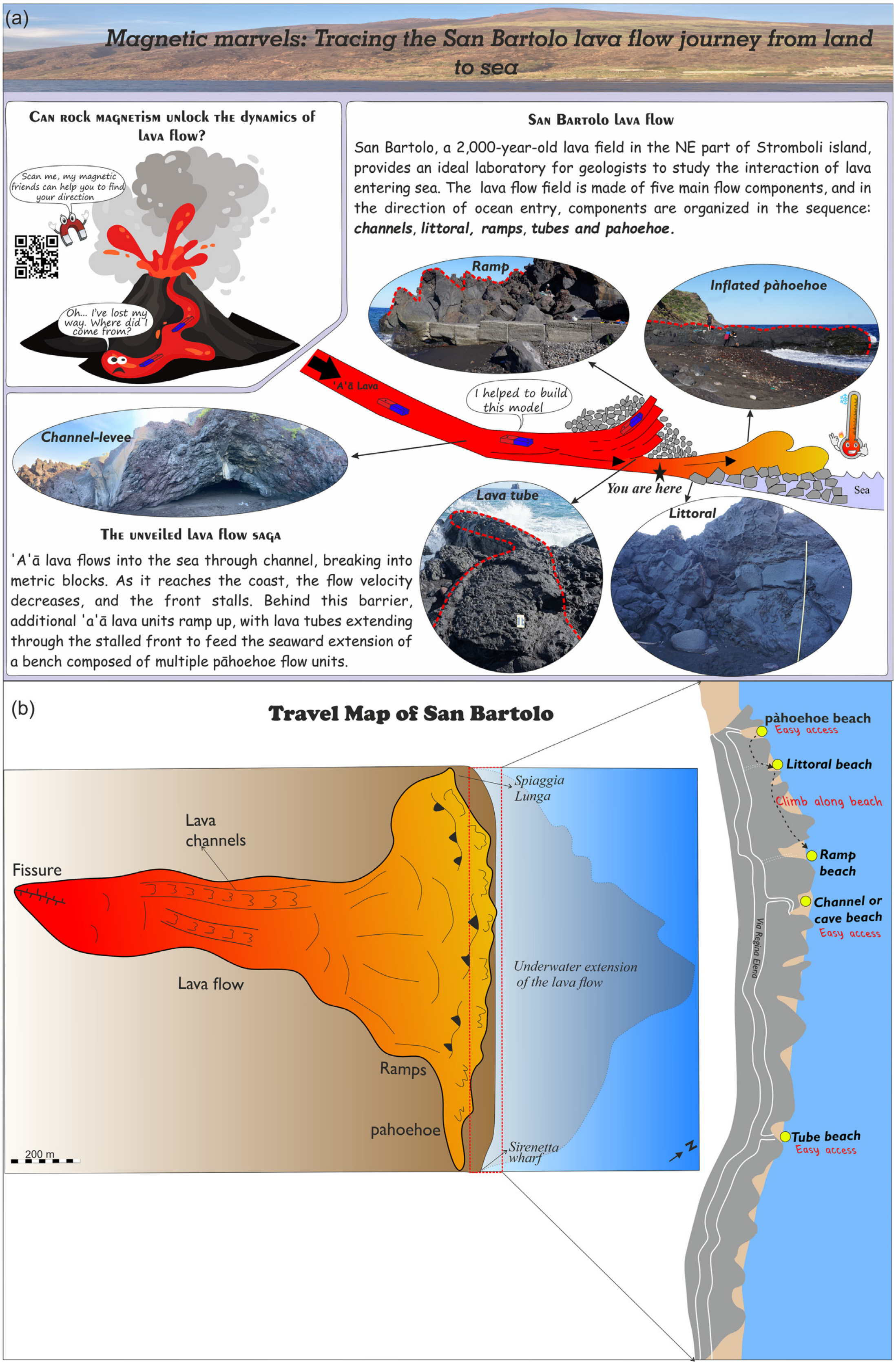


Fig. 15. a. Proposed model of the interpretative panel for the San Bartolo lava flow. This could be a general one, and for each site, only the image of that site could be employed. b. The map of San Bartolo, with basic tourist information on beach names and how to get to the beaches, can be included in information leaflets for local hotels and guides. This map gently draws the reader into the area to be presented with basic information. This sets the scene for a more detailed and in-depth interaction if the visitor so wishes.

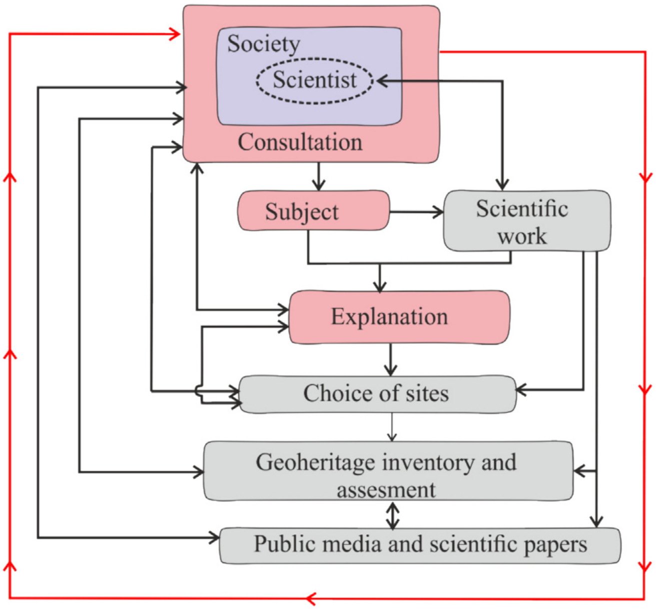


Fig. 16. Graphical system diagram showing the information and work flow in the method we implemented. It shows how each component is related and how the whole process is circular, with the possibility to be joined at any stage.

Following this implementation, we aim to assess the effectiveness of our method. This evaluation will likely involve soliciting feedback from tourists through a QR code questionnaire and conducting in-person surveys to gather opinions from both visitors and those involved in the tourism sector.

This method could be useful for researchers beginning a study to allow them to initiate discourse with a wider public from the start, which could reinforce the scientific work open up to have more societal relevance and social impact. It could open the way for participatory science. Practically, it could aid the development of geosites as geo-tourist attractions, enhancing economic benefit, respect for sites (that comes from knowledge) and thus better protection.

Finally, we propose a two-pronged approach. The first is to develop simple, clear, and understandable definitions of scientific methods and processes through a step-by-step approach. The second is to structure the work using a geoheritage inventory approach, providing the best strategy for subsequent outreach and interaction with visitors and local stakeholders.

At all stages of this project, we have chosen to consult and involve the general public, including non-scientific colleagues and others, in order to remain connected to our public and to develop a general understanding of the AMS technique. Something once difficult to grasp now has the potential to become a concept everyone can share.

Ethical statement

Ethical approval is not applicable, because this article does not contain any studies with human or animal subjects. The authors confirm that no ethical issues are linked to this manuscript and the underlying study. Verbal informed consent was obtained from all subjects before the study.

CRediT authorship contribution statement

Rasia Shajahan: Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation. **Benjamin van Wyk de Vries:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Investigation, Conceptualization. **Elena Zanella:** Writing – review & editing, Supervision, Resources, Formal analysis, Data curation. **Andrew Harris:** Writing – review & editing, Supervision, Resources, Formal analysis, Data curation.

Declaration of competing interest

One of the authors, Benjamin van Wyk de Vries, is an Editor-in-Chief for International journal of geoheritage and parks, and was not involved in the editorial review or the decision to publish this article. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This project is a part of Rasia Shajahan's PhD project. The part of this thesis was funded by Ministero dell'Università e della Ricerca (MUR) with ex-60% with 60% allocated to Elena Zanella and 10% of the PhD grants budget assigned to Rasia Shajahan. This work is a contribution to the UNESCO International Geosciences Prgramme (IGCP) Project No. 692 'Geoheritage for Geohazard Resilience' (www.geopoderes.com). We are thankful to our colleagues, students and tourist who participated in our questionnaire and gave feedback.

Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijgeop.2024.07.007.

References

Allan, M., Dowling, R. K., & Sanders, D. (2015). The motivations for visiting geosites: The case of crystal cave, Western Australia. *Geojournal of Tourism and Geosites*, *16*, 141–152.

Arrighi, S., Rosi, M., Tanguy, J. -C., & Courtillot, V. (2004). Recent eruptive history of Stromboli (Aeolian Islands, Italy) determined from high-accuracy archeomagnetic dating. *Geophysical Research Letters*, *31*(19), L19603. https://doi.org/10.1029/2004GL020627.

Besson, J. C. (1978). *Les formations volcaniques du versant oriental du massif du Mont-dore (massif central français):(Feuille 1/25 000 Veyre-Montonn° 5-6) [The volcanic formations on the eastern slope of the Mont-Dore Massif (French Massif Central): (Sheet 1/25,000 Veyre-Monton no. 5-6)].* (Doctoral dissertation)Université de Clermont-Ferrand, France.

Bityukova, L., Scholger, R., & Birke, M. (1999). Magnetic susceptibility as indicator of environmental pollution of soils in Tallinn. *Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy*, *24*(9), 829–835. https://doi.org/10.1016/S1464-1895(99)00122-2.

Bonali, F., Russo, E., Vitello, F., Antoniou, V., Marchese, F., Fallati, L., Bracchi, V., Corti, N., Savini, A., Whitworth, M., & Drymoni, K. (2021). How academics and the public experienced immersive virtual reality for geo-education. *Geosciences*, *12*(1), 9. https://doi.org/10.3390/geosciences12010009.

Borradaile, G. J., & Jackson, M. (2004). Anisotropy of magnetic susceptibility (AMS): Magnetic petrofabrics of deformed rocks. *Geological Society, London, Special Publications*, *238*(1), 299–360. https://doi.org/10.1144/GSL.SP.2004.238.01.18.

Bouchez, J. L. (1997). Granite is never isotropic: An introduction to AMS studies of granitic rocks. In J. L. Bouchez, D. H. W. Hutton, & W. E. Stephens (Eds.), *Granite: From segregation of melt to emplacement fabrics. Vol. 8*. (pp. 95–112). Dordrecht: Springer. https://doi.org/10.1007/978-94-017-1717-5_6.

Božić, S., & Tomić, N. (2015). Canyons and gorges as potential geotourism destinations in Serbia: Comparative analysis from two perspectives—general geotourists' and pure geotourists'. *Open Geosciences*, *7*(1), 531–546. https://doi.org/10.1515/geo-2015-0040.

Branca, S., Coltelli, M., De Beni, E., & Wijbrans, J. (2008). Geological evolution of Mount Etna volcano (Italy) from earliest products until the first central volcanism (between 500 and 100 ka ago) inferred from geochronological and stratigraphic data. *International Journal of Earth Sciences*, *97*(1), 135–152. https://doi.org/10.1007/s00531-006-0152-0.

Branca, S., Coltelli, M., Groppelli, G., & Lentini, F. (2011). Geological map of Etna volcano, 1:50,000 scale. *Italian Journal of Geosciences*, *130*(3), 265–291. https://doi.org/10.3301/IJG.2011.15.

Brousse, R. (1971). *Magmatologie du volcanisme néogène et quaternaire du massif central in symposium Géologie, géomorphologie et structure profonde du massif central Français [Magmatology of Neogene and quaternary volcanism of the massif central in the symposium on geology, geomorphology, and deep structure of the French massif central] (pp. 377-478)*. Clermont-Ferrand: Plein Air Service.

Calvari, S., Marotta, E., Vicari, A., Famiglietti, N. A., Ganci, G., Miraglia, L., ... Peluso, R. (2023). *The San Bartolo lava flow field along the northeast flank of Stromboli Volcano: A preliminary study for field survey*. https://doi.org/10.5281/ZENODO.7760868.

Cañón-Tapia, E., & Chávez-Álvarez, M. J. (2004). Theoretical aspects of particle movement in flowing magma: Implications for the anisotropy of magnetic susceptibility of dykes. *Geological Society, London, Special Publications*, *238*(1), 227–249. https://doi.org/10.1144/GSL.SP.2004.238.01.15.

Dóniz-Páez, J., Beltrán-Yanes, E., Becerra-Ramírez, R., Pérez, N. M., Hernández, P. A., & Hernández, W. (2020). Diversity of volcanic geoheritage in the Canary Islands, Spain. *Geosciences*, *10*(10), 390. https://doi.org/10.3390/geosciences10100390.

Dowling, R. K. (2011). Geotourism's global growth. *Geoheritage*, *3*(1), 1–13. https://doi.org/10.1007/s12371-010-0024-7.

Ellwood, B. B. (1980). Application of the anisotropy of magnetic susceptibility method as an indicator of bottom-water flow direction. *Marine Geology*, *34*(3–4), M83–M90. https://doi.org/10.1016/0025-3227(80)90066-3.

Ferlito, C., & Nicotra, E. (2010). The dyke swarm of Mount Calanna (Etna, Italy): An example of the uppermost portion of a volcanic plumbing system. *Bulletin of Volcanology*, *72*(10), 1191–1207. https://doi.org/10.1007/s00445-010-0398-z.

Ferrari, L., Calvari, S., Coltelli, M., Innocenti, F., Pasquarè, G., Pompilio, M., ... Villa, I. (1989). Nuovi dati geologici e strutturali sulla Valle di Calanna, Etna: implicazioni per l'evoluzione del vulcanismo etneo [New geological and structural data on the Calanna Valley, Etna: implications for the evolution of Etna's volcanism]. *Bollettino della Società Entomologica Italiana*, *2*, 849–860.

Fuller, M. D. (1963). Magnetic anisotropy and paleomagnetism. *Journal of Geophysical Research*, *68*(1), 293–309. https://doi.org/10.1029/JZ068i001p00293.

Graham, J. W. (1954). Magnetic anisotropy, an unexploited petrofabric element. *Geological Society of America Bulletin*, *65*, 1257–1258.

Granados-Bolaños, S., Quesada-Román, A., & Alvarado, G. E. (2021). Low-cost UAV applications in dynamic tropical volcanic landforms. *Journal of Volcanology and Geothermal Research*, *410*, Article 107143. https://doi.org/10.1016/j.jvolgeores.2020.107143.

Granar, L. (1958). Magnetic measurements on Swedish varved sediments. *Arkiv för Geofysik*, *3*(1), 1–40.

Guilbaud, M. N., Ortega-Larrocea, M. D. P., Cram, S., & van Wyk de Vries, B. (2021). Xitle volcano geoheritage, Mexico City: Raising awareness of natural hazards and environmental sustainability in active volcanic areas. *Geoheritage*, *13*(1), 6. https://doi.org/10.1007/s12371-020-00525-9.

Gurioli, L., Pareschi, M. T., Zanella, E., Lanza, R., Deluca, E., & Bisson, M. (2005). Interaction of pyroclastic density currents with human settlements: Evidence from ancient Pompeii. *Geology*, *33*(6), 441–444. https://doi.org/10.1130/G21294.1.

Jelinek, V. (1981). Characterization of the magnetic fabric of rocks. *Tectonophysics*, *79*(3–4), T63–T67. https://doi.org/10.1016/0040-1951(81)90110-4.

Jonić, V. (2018). Comparative analysis of Devil's town and Bryce canyon geosites by applying the modified geosite assessment model (M-GAM). *Zbornik Radova Departmana Za Geografiju, Turizam i Hotelijerstvo*, *47–2*, 113–125. https://doi.org/10.5937/ZbDght1802113J.

Kent, D. V., & Lowrie, W. (1975). On the magnetic susceptibility anisotropy of deep-sea sediment. *Earth and Planetary Science Letters*, *28*(1), 1–12. https://doi.org/10.1016/0012-821X(75)90067-9.

Khalifa, K. (2013). The role of explanation in understanding. *The British Journal for the Philosophy of Science*, *64*(1), 161–187. https://doi.org/10.1093/bjps/axr057.

Khan, M. A. (1962). The anisotropy of magnetic susceptibility of some igneous and metamorphic rocks. *Journal of Geophysical Research*, *67*(7), 2873–2885. https://doi.org/10.1029/JZ067i007p02873.

Lesage, L. (2013). *Étude morphologique, pétrologique et géochimique des coulées de laves de Thônes le Vieux et de Farges [Morphological, petrological, and geochemical study of the lava flows of Thônes le Vieux and Farges] (Master's thesis)*. Université Blaise Pascal, Clermont-Ferrand, France.

Li, S., van Hinsbergen, Shen, Z., Najman, Y., Deng, C., & Zhu, R. (2020). Anisotropy of magnetic susceptibility (AMS) analysis of the Gonjo Basin as an independent constraint to date Tibetan shortening pulses. *Geophysical Research Letters*, *47*(8), Article e2020GL087531.

Loock, S., Diot, H., Van Wyk De Vries, B., Launeau, P., Merle, O., Vadeboin, F., & Petronis, M. S. (2008). Lava flow internal structure found from AMS and textural data: An example in methodology from the Chaîne des Puys, France. *Journal of Volcanology and Geothermal Research*, *177*(4), 1092–1104. https://doi.org/10.1016/j.jvolgeores.2008.08.017.

Matasova, G., Petrovský, E., Jordanova, N., Zykina, V., & Kapička, A. (2001). Magnetic study of late Pleistocene loess/palaeosol sections from Siberia: Palaeoenvironmental implications. *Geophysical Journal International*, *147*(2), 367–380. https://doi.org/10.1046/j.0956-540x.2001.01544.x.

McGuire, W. J. (1982). Evolution of the Etna volcano: Information from the southern wall of the Valle Del Bove caldera. *Journal of Volcanology and Geothermal Research*, *13*(3–4), 241–271. https://doi.org/10.1016/0377-0273(82)90053-1.

Németh, K., Casadevall, T., Moufti, M. R., & Marti, J. (2017). Volcanic geoheritage. *Geoheritage*, *9*(3), 251–254. https://doi.org/10.1007/s12371-017-0257-9.

Nicotra, E., Ferlito, C., Viccaro, M., & Cristofolini, R. (2011). Volcanic geology and petrology of the Val Calanna succession (Mt. Etna, Southern Italy): Discovery of a new eruptive center. *Periodico di Mineralogia*, *80*(2), 287–307. https://doi.org/10.2451/2011PM0021.

Petronis, M. S., Delcamp, A., & Van Wyk De Vries, B. (2013). Magma emplacement into the Lemptégy scoria cone (Chaîne des Puys, France) explored with structural, anisotropy of magnetic susceptibility, and paleomagnetic data. *Bulletin of Volcanology*, *75*(10), 753. https://doi.org/10.1007/s00445-013-0753-y.

Petronis, M. S., Van Wyk De Vries, B., & Garza, D. (2019). The leaning Puy de Dôme (Auvergne, France) tilted by shallow intrusions. *Volcanica*, *2*(2), 161–189. https://doi.org/10.30909/vol.02.02.161186.

Potter, D. K., & Stephenson, A. (1988). Single-domain particles in rocks and magnetic fabric analysis. *Geophysical Research Letters*, *15*(10), 1097–1100. https://doi.org/10.1029/GL015i010p01097.

Quesada-Román, A., & Pérez-Umaña, D. (2020). Tropical paleoglacial geoheritage inventory for geotourism management of Chirripó National Park, Costa Rica. *Geoheritage*, *12*(3), 58. https://doi.org/10.1007/s12371-020-00485-0.

Quesada-Román, A., Torres-Bernhard, L., Ruiz-Álvarez, M. A., Rodríguez-Maradiaga, M., Velázquez-Espinoza, G., Espinosa-Vega, C., ... Rodríguez-Bolaños, H. (2021). Geodiversity, geoconservation, and geotourism in Central America. *Land*, *11*(1), 48. https://doi.org/10.3390/land11010048.

Quesada-Valverde, M. E., & Quesada-Román, A. (2023). Worldwide trends in methods and resources promoting geoconservation, geotourism, and geoheritage. *Geosciences*, *13*(2), 39. https://doi.org/10.3390/geosciences13020039.

Rochette, P., Aubourg, C., & Perrin, M. (1999). Is this magnetic fabric normal? A review and case studies in volcanic formations. *Tectonophysics*, *307*(1–2), 219–234. https://doi.org/10.1016/S0040-1951(99)00127-4.

Romano, R. (1982). Succession of the volcanic activity in the Etnean area. *Memorie della Societa Geologica Italiana*, *23*, 27–48.

Romano, R., & Guest, J. (1979). Volcanic geology of the summit and northern flank of Mount Etna, Sicily. *Bollettino della Societa Geologica Italiana*, *98*(2), 189–215.

Shajahan, R., Harris, A., Mana, S., Nicotra, E., Test, C. R., ... Zanella, E. (2024). Emplacement and flow dynamics in a small volcanic dyke swarm: The example of Mount Calanna (Etna, Italy). *Journal of Volcanology and Geothermal Research*, *449*, 108069. https://doi.org/10.1016/j.jvolgeores.2024.108069.

Shajahan, R., Harris, A. J., Zanella, E., Gurioli, L., Test, C. R., Calvari, S., & Drovanti, L. (2024). When the lava meets the sea: Emplacement of the 2–4 ka San Bartolo lava flow field, Stromboli volcano (Italy). *Bulletin of Volcanology*, *86*(5), 1–24. https://doi.org/10.1007/s00445-024-01743-7.

Speranza, F., Pompilio, M., D'Ajello Caracciolo, F., & Sagnotti, L. (2008). Holocene eruptive history of the Stromboli volcano: Constraints from paleomagnetic dating. *Journal of Geophysical Research: Solid Earth*, *113*(B9), B09101. https://doi.org/10.1029/2007JB005139.

Suzuki, D. A., & Takagi, H. (2018). Evaluation of geosite for sustainable planning and management in geotourism. *Geoheritage*, *10*(1), 123–135. https://doi.org/10.1007/s12371-017-0225-4.

Tarling, D., & Hrouda, F. (1993). *Magnetic anisotropy of rocks*. Dordrecht: Springer Science & Business Media.

Tomić, N., & Božić, S. (2014). A modified geosite assessment model (M-GAM) and its application on the lazar canyon area (Serbia). *International Journal of Environmental Research*, *8*(4), 1041–1052.

Vincent, P. M. (1980). Volcanisme et chambres magmatiques: l'exemple des Monts Dore [Volcanism and magma chambers: The example of the Monts Dore]. *Mémoires de la Société Géologique de France*, *10*, 71–85.

Zanella, E., Gurioli, L., Pareschi, M. T., & Lanza, R. (2007). Influences of urban fabric on pyroclastic density currents at Pompeii (Italy): 2. Temperature of the deposits and hazard implications. *Journal of Geophysical Research: Solid Earth*, *112*(B5), B05214. https://doi.org/10.1029/2006JB004775.

Zhu, Z. M., Zhang, S. H., Tang, C. Y., Li, H. Y., Xie, S. C., Ji, J. L., & Xiao, G. Q. (2012). Magnetic fabric of stalagmites and its formation mechanism. *Geochemistry, Geophysics, Geosystems*, *13*(6), Q06006. https://doi.org/10.1029/2011GC003869.