Assessment and management of geoheritage in active volcanic areas:
threats, challenges, and opportunities

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Assessment and management of geoheritage in active volcanic areas: threats, challenges, and opportunities

ABSTRACT

Volcanic activity, present since the formation of Earth, has left a rich geological legacy in the form of beautiful landscapes that houses impressive biodiversity. While active volcanic regions are captivating due to their geological diversity, they also carry risks and harmful effects, including the volcanic hazards and weather events. Nevertheless, they also offer significant benefits to society through resources and economic activities such as geotourism. Many volcanic sites have emerged as important national and international tourist destinations, some under the auspices of organizations like UNESCO, which seek their protection and promote their sustainable use, or the IUGS, highlighting their international scientific importance.

Managing the geoheritage of active volcanic areas requires ensuring the safety of visitors and preserving the sustainability of these environments. Planning and collaboration among local authorities, scientists, tourism managers, and communities are essential to mitigate risks and improve the management of these sites. It is crucial that transparent communication about volcanic risks should not be a barrier to geotourism, but rather should be an opportunity to strengthen visitor confidence by demonstrating that safety measures are necessary and have been implemented. Furthermore, involving local populations will enhance resilience and the geotourism experience.

Therefore, this dissertation proposes guidelines for evaluating geosites in active volcanic areas, considering the risk to visitors and integrating this into geoheritage inventories. A comprehensive management plan is proposed, considering existing hazards, to anticipate and determine which geosites are safe, which are on alert, and which should be restricted immediately, with clear guidelines for territorial managers. Geoeducation and safe geotourism are highlighted as key aspects. These not only enrich the visitor experience but also contribute to the conservation of geological heritage, promote research, stimulate local economic development, and ensure that everyone can continue to enjoy volcanic landscapes safely.

Key words: Safe geotourism, volcanic geoheritage, visitor risk assessment, management plan, geoconservation, geoeducation.

Avaliação e gestão do património geológico em áreas vulcânicas ativas: ameaças, desafios, e oportunidades

RESUMO

A atividade vulcânica, presente desde a formação da Terra, deixou um importante legado geológico na forma de belas paisagens que abrigam uma biodiversidade impressionante. Embora as regiões vulcânicas ativas sejam cativantes devido à sua geodiversidade, elas também trazem riscos e efeitos prejudiciais, incluindo os perigos de erupções e eventos climáticos. No entanto, também oferecem benefícios significativos à sociedade por meio de recursos e atividades econômicas, como o geoturismo. Muitos locais vulcânicos surgiram como importantes destinos turísticos nacionais e internacionais, alguns sob os auspícios de organizações como a UNESCO, que buscam sua proteção e promovem seu uso sustentável, ou a IUGS, destacando sua importância científica internacional.

Gerir o patrimônio geológico de áreas vulcânicas ativas requer garantir a segurança dos visitantes e preservar a sustentabilidade desses ambientes. Planejamento e colaboração entre autoridades locais, cientistas, gestores de turismo e comunidades são essenciais para mitigar riscos e melhorar a gestão desses locais. É crucial que a comunicação transparente sobre os riscos vulcânicos não seja uma barreira ao geoturismo, mas sim uma oportunidade para fortalecer a confiança dos visitantes, demonstrando que as medidas de segurança necessárias foram implementadas. Além disso, envolver as populações locais aprimorará a resiliência e a experiência do geoturismo.

Esta dissertação propõe diretrizes para avaliar geossítios em áreas vulcânicas ativas, considerando o risco para os visitantes e integrando-o aos inventários de património geológico. É proposto um plano de gestão abrangente, considerando os perigos existentes, para antecipar e determinar quais geossítios são seguros, quais estão em alerta e quais devem ser restritos imediatamente, com diretrizes claras para os gestores territoriais. A geoeducação e o geoturismo seguro são destacados como aspetos-chave. Estes não apenas enriquecem a experiência do visitante, mas também contribuem para a conservação do património geológico, promovem a pesquisa, estimulam o desenvolvimento económico local e garantem que todos possam continuar a desfrutar de paisagens vulcânicas com segurança.

Evaluación y gestión del geopatrimonio en áreas volcánicas activas: amenazas, desafíos, y oportunidades

RESUMEN

La actividad volcánica, presente desde la formación de la Tierra, ha dejado un rico legado geológico en forma de hermosos paisajes que albergan una impresionante biodiversidad. Si bien las regiones volcánicas activas son cautivadoras por su diversidad geológica, también conllevan riesgos y efectos perjudiciales, incluidos los peligros de las erupciones y eventos meteorológicos. No obstante, también ofrecen beneficios significativos a la sociedad, a través de recursos y actividades económicas como el geoturismo. Muchos sitios volcánicos han surgido como importantes destinos turísticos nacionales e internacionales, algunos bajo los auspicios de organizaciones como la UNESCO, que buscan su protección y promueven su uso sostenible, o la IUGS, destacando su importancia científica internacional.

Gestionar el patrimonio geológico de áreas volcánicas activas necesita garantizar la seguridad de los visitantes y preservar la sostenibilidad de estos entornos. La planificación y la colaboración entre las autoridades locales, científicos, gestores turísticos y comunidades, son esenciales para mitigar riesgos y mejorar la gestión de estos sitios. Es crucial que la comunicación transparente sobre los riesgos volcánicos no sea una barrera para el geoturismo, sino una oportunidad para fortalecer la confianza de los visitantes al demostrar que se han implementado las medidas de seguridad necesarias. Además, involucrar a las poblaciones locales mejorará el concepto de resiliencia y la experiencia del geoturismo.

Por lo tanto, esta tesis propone directrices para la evaluación de geositios en áreas volcánicas activas, considerando el riesgo para los visitantes y que sea integrado en los inventarios de patrimonio geológico. Se propone un plan de gestión integral, considerando los peligros existentes, para anticipar y determinar qué geositios son seguros, cuáles están en alerta y cuáles deben ser restringidos de inmediato, con pautas claras para los gestores del territorio. La geoeducación y el geoturismo seguro se destacan como aspectos clave. Estos no solo enriquecen la experiencia de los visitantes, sino que también contribuyen a la conservación del patrimonio geológico, promueve la investigación, estimulan el desarrollo económico local y garantiza que todos puedan seguir disfrutando de los paisajes volcánicos de manera segura.

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I. INTRODUCTION

Volcanoes are vast geological formations that have been present since the Earth's formation billions of years ago. They have shaped remarkable landscapes of geological beauty and as geoheritage sites, featuring structures and deposits from recent eruptions that are significant for scientific and educational research, as well as popular tourist destinations on both national and international levels. Many active volcanic sites are affiliated with international organizations that grant them global recognition and provide protection for their natural properties. Among these initiatives are the UNESCO Global Geoparks, which highlight sites of scientific and cultural importance, promoting sustainable development in collaboration with local communities. Additionally, some volcanic sites are on the World Heritage List for their exceptional geological characteristics, recognized under criterion (viii) (Migoń 2018; Casadevall et al. 2019b; Keever and Narbonne 2021).

The recent compilation of the First 100 Geological Heritage Sites by the International Union of Geological Sciences (IUGS) aims to promote key geological heritage sites of international scientific significance (Hilario et al. 2022). Furthermore, the establishment of the "Commission on Volcano Geoheritage and Protected Volcanic Landscapes" by the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) serves as a knowledge center for the development of geoconservation, geoeducation, and scientifically accurate programs. This initiative aims to ensure a more comprehensive representation of the IAVCEI and strengthen its geoprotection efforts in volcanic areas (Showstack 2015; Németh et al. 2017).

A volcanic eruption presents one of the most captivating natural phenomena to witness, but it also carries significant hazards. Its impact can extend over a radius of tens of kilometers and may even lead to changes of the global climate. Volcanoes are geologically active, even when not in eruption, and in conjunction with weather events, originate many addition hazards. The presence of geosites in regions with active volcanoes highlights the importance of implementing additional or complementary management strategies tailored to the specific type and activity level of the volcano. This entails close collaboration with institutions engaged in geological research and volcano monitoring, to understand the eruptive history of the volcano, utilize hazard maps, and stay informed about its current activity for the safety of tourists and local residents. Furthermore, promoting geoeducation on volcanic hazards through geotourism plays a vital role in preparing the local population and ensuring the safety of communities and tourist. This approach helps minimize vulnerability (the potential for harm to a person or infrastructure) and promote resilience (the ability to withstand shock and adapt to changes in a beneficial way) in the face of potential hazards. Currently, many new volcanic geoheritage projects are in progress. Some of these projects focus on volcanic regions known for their explosive and effusive nature. Some are related with the UNESCO's International Geosciences Programme (IGCP) project 692 – "Geoheritage for geohazard resilience". For instance, research is being conducted on Misti Volcano and Chachani in Peru (South America), which have a history of Vulcanian to Plinian eruptions. Similarly, investigations are underway at Concepción volcano in Nicaragua (Central America) in a geopark candidate project, with the primary goal of working on community resilience through a bottom-up approach using the support of local government in the face of volcanic hazards, as well as promoting the protection of geological resources.

This research highlights the importance and need to consider volcanic hazard factors and their appropriate management in geoheritage sites. It advocates for incorporating the visitor risk assessment into existing inventories, which already evaluate scientific, educational, and tourist uses, as well as the vulnerability of geosites. Additionally, it proposes using geoheritage as a tool for geoeducation in risk management and promoting safe geotourism, addressed to visitors, local communities and workers. This proposal serves as a customizable framework adaptable to the realities of each volcanic territory. Thus, the objectives and vision of geoheritage management will not only focus on geoconservation and sustainable use of the territory but also on safeguarding visitor safety during emergencies without completely restricting the use of this natural resource.

1.1. Problem statement

Volcanoes have always been considered fascinating sites, showcasing the immense power of nature through their eruptions. In geoheritage sites with active volcanic activity, which serve as tourist, educational, and scientific destinations, the primary threats come directly from the volcanoes themselves. These threats include volcanic hazards that pose risks to visitors, site workers, and local populations. However, some of these protected sites may not fully acknowledge their status as active areas with potential risks such as volcanic eruptions, gas emissions, landslides, lahars, and other non-eruptive hazards, which might not be adequately addressed in their management plans.

Therefore, managing these active sites, which attract thousands of tourists each year, entails the responsibility of being prepared by identifying geosites located in vulnerable areas as a tool for quick decision-making by administrators, establishing an alert system for visitors, and forming partnerships with scientific and technical entities that study volcanoes and others. Finally, take advantage of geotourism to promote geoeducation and resilience by raising awareness of volcanic hazards can enhance visitor safety.

The main research question for this dissertation is: How can geotourism be developed safely in active volcanic areas, particularly those experiencing or projected to experience high tourist activity and lacking specific assessment and management strategies to address volcanic hazards?

1.2. Objectives

The main objective of this dissertation is to develop guidelines to improve the assessment and management plans of geosites in active volcanic areas, considering the hazards posed by volcanic eruptions and non-eruptive events to visitors. These guidelines are expected to promote safe volcanic geotourism, strengthen geoeducation efforts, and enhance resilience to volcanic hazards. The specific objectives are:

- To integrate criteria that address volcanic hazards for visitors into holistic assessment and management guidelines for geosites located in active volcanic areas;
- To promote community involvement in geoheritage management and resilience in the development of geotourism in volcanoes;
- To advance geoeducation in geoheritage and volcanic hazards through geotourism.

II. CONCEPTS AND BACKGROUND

2.1. Vulcanology

Volcanology is the scientific field dedicated to studying volcanoes, encompassing their eruptions, structure, petrology, origins, and the movement of magma from the mantle through the Earth's crust, leading to surface eruptions (Sigurdsson 1999). Volcanology also includes the social and cultural aspects of volcanoes, their resources and economic benefits. Moreover, certain volcanic processes pose significant natural hazards, while others offer notable benefits to society. Geologists, particularly volcanologists, are central to the investigation of volcanoes and play a vital role in understanding their connection to terrestrial seismic events like faults, earthquakes and plate tectonics.

The Earth is in constant motion. Mountain chains form, grow, and erode; volcanoes erupt and eventually become extinct, and earthquakes occur. All of these phenomena result from the movement of lithosphere tectonic plates, and the convection of the asthenosphere below the lithosphere (Van Wyk de Vries and Van Wyk de Vries 2018). Tectonic plates and mantle convection are fundamental to magmatism, producing magma that forms the lithosphere (Figure 1). Approximately 90% of magma is generated at divergent plate boundaries like mid-ocean ridges. Continental rifts can evolve into oceanic spreading systems. Hotspots are areas of rising asthenospheric convection or mantle melting, producing various volcanic fields. At convergent plate boundaries, subduction of oceanic lithosphere beneath the continental plate leads to mantle melting and volatile release; subsequently, magma rises, producing volcanism and igneous plumbing systems, varying depending on the tectonic environment (Van Wyk de Vries and Van Wyk de Vries 2018). According to the Smithsonian Institution (2024), an active volcano is one that has shown eruptive activity during the Holocene epoch, within the last 11,000 years. It is estimated that there are around 1,350 active volcanoes worldwide.

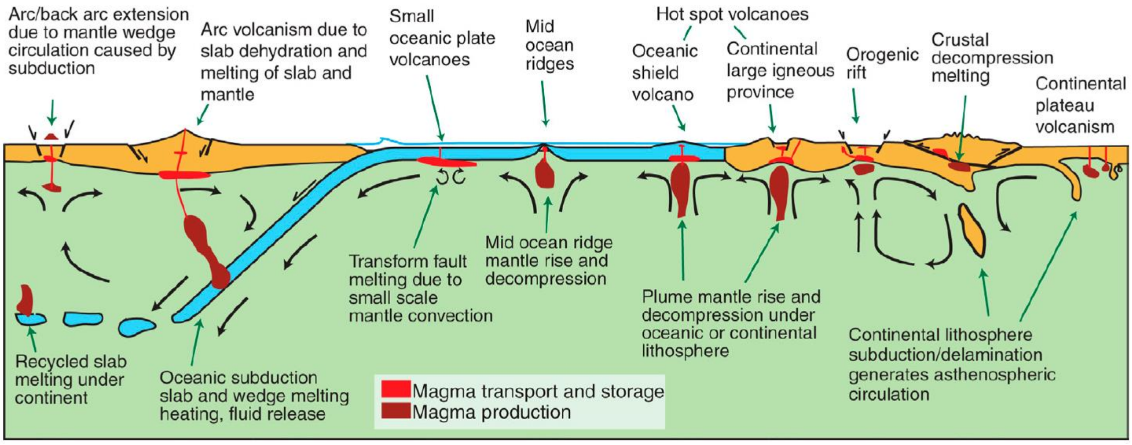


Figure 1. Plate tectonics and magma production (Van Wyk de Vries and Van Wyk de Vries 2018).

2.1.1. Volcanism and volcanic products

A volcano is a significant geological structure through which magma emerges in various types of eruptions above the Earth's surface. According to Myers et al. (1997) over the past 200 years, more than 400 volcanoes worldwide have erupted one or more times, with some of these eruptions resulting in thousands of casualties and extensive property damage. The most active volcanic regions are concentrated in the Pacific Ring of Fire, which spans islands in the South, Western, and North Pacific, as well as Japan, extensive areas along the western edge of North America, Central America, the Caribbean, and large stretches of South America along the Andes Mountains. Additionally, active volcanic zones are found in eastern and western Africa and southern Europe (Myers et al. 1997).

Eruptions can proceed in the following sequence, with the expulsion of different volcanic products depending on the magnitude of the eruption (Figure 2). All these events can occur or only some of them independently. First, due to some alteration of the chamber that causes changes in the chemistry of the magma, along with increased pressure and temperature, it rises from the depths of the volcano, leading to explosive eruptions with large emissions of pyroclasts (tephra and rock fragments) into the atmosphere, forming a large eruptive column composed of gases, ashes, and pyroclasts of various sizes (Stovall et al. 2019). The largest fragments are referred to as bombs or ballistic projectiles (>64 mm), due to their density; they can fall as far as 4 kilometers from the crater or vent. Smaller fragments, known as lapilli (64 - 2 mm), and even finer particles like ash (<2 mm) can move longer distances, even reach other continents or affect global climate (Myers et al. 1997; Stovall et al. 2019).

When the column becomes unstable, it collapses, creating hot pyroclastic density currents (PDC) that descend the volcano's flanks at high speeds and temperatures, sweeping everything in their path. These can melt snow and ice or enter rivers to create lahars. When the volcano's eruption is more effusive and there are lava flows, it can flow downhill or form lava domes when it is very viscous and cools in the crater. When there is an accumulation of pressure and the dome collapses or explodes, PDCs can also occur (Stovall et al. 2019).

Even when a volcano is not erupting, landslides or debris avalanches can occur due to gravity, and lahars during rainy times. In stratovolcanoes and caldera systems that host hot springs, fumaroles, and other thermal features, hot rocks and steam explosions called hydrothermal explosions can occur at any time. Volcanic gases are also present, including carbon dioxide, sulfur dioxide, hydrogen sulfide, and fluorine. Many of these gases are toxic to both human and animal health and can impact Earth’s climate while also contributing to the formation of acid rain (Myers et al. 1997; Stovall et al. 2019).

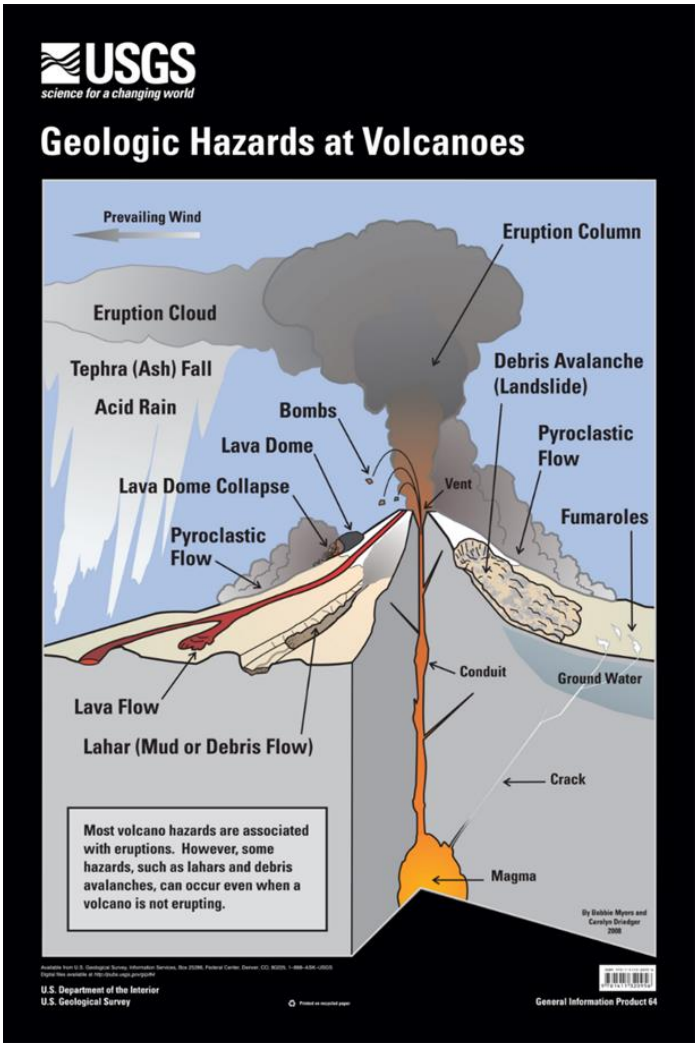


Figure 2. Volcanic hazards defined by the United States Geological Survey (USGS, 2008).

Several notable volcanic eruptions have demonstrated the release of primary volcanic products, including ash falls and column collapses. For instance, at the Ubinas volcano in Peru (Figure 3a), a small pyroclastic flow occurred in August 2023 following ash falls and column collapses that exceeded 5 km in height. These eruptions dispersed ballistic projectiles and ash in a south, southeast, and southwest direction, impacting nearby towns and agricultural areas (INGEMMET, 2023). Significant volcanic gas emissions have also been observed, particularly at Nicaragua's Masaya Volcanic Complex (Figure 3b). The Santiago crater emits approximately 2,213 tons per day of sulphur dioxide, monitored by INETER with a station located 9 km east of the volcano (ineter.gob.ni). Lava dome formation was documented at the Nevados de Chillan volcano in Chile in April 2018 (Figure 3c), with growth monitored by Sernageomin (National geology and mining survey of Chile).

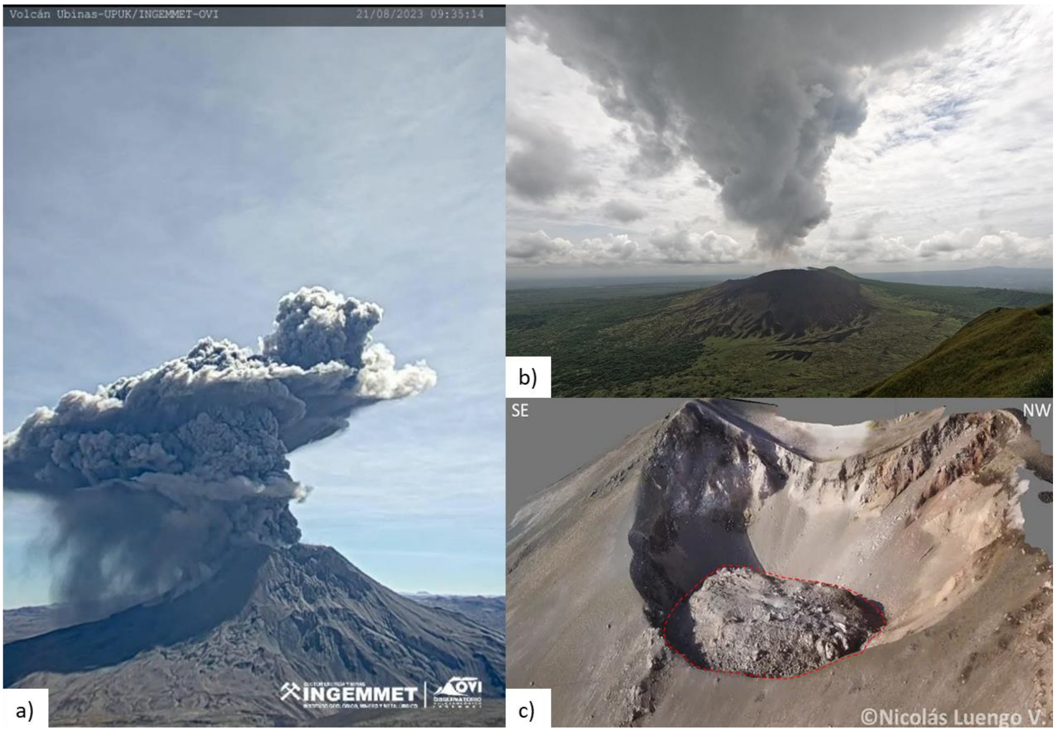


Figure 3. a) Ash fall of Ubinas volcano - Peru Photo: INGEMMET. b) Gas emission from the Masaya volcano – Nicaragua Photo: Carla Arias. c) Formation of lava domes in the Nevados de Chillan volcano – Chile Photo: Nicolás Luengo, University of Concepción.

The September 1984 eruption of the Mayon volcano in the Philippines resulted in large pyroclastic flows descending the southeast flank of the volcano (Figure 4a), caused by the collapse of a column reaching 15 km in height. Although the eruption triggered evacuations of over 73,000 people from hazard zones, no casualties were reported, thanks to early warnings from scientists at the Philippine Institute of Volcanology and Seismology.

In the USA, during the May 18, 1980 eruption of Mount Saint Helens (Figure 4c), a massive debris avalanche occurred, considered the largest in recorded history. The eruption, rated VEI 5, was triggered by a magnitude 5.1 earthquake that destabilized the volcano's northern flank, resulting in lateral explosions of gases, molten rock, and water vapor from the ice cap. This event led to significant pyroclastic flows and lahars that devastated areas along the Toutle river. The eruption dispersed ash around the globe by May 29, according to the Smithsonian Institution (2024).

Tragically, the Nevado del Ruiz volcano in Colombia produced large lahars in November 1985 (Figure 4b), which destroyed the entire city of Armero, located 50 km from the volcano. This disaster claimed over 20,000 lives out of the city's 29,000 inhabitants, along with an additional 3,000 casualties from nearby municipalities. The lahars formed as a result of melting glaciers mixing with pyroclastic material, descending the slopes of Nevado del Ruiz at speeds of 60 km/h (Lowe et al. 1986).

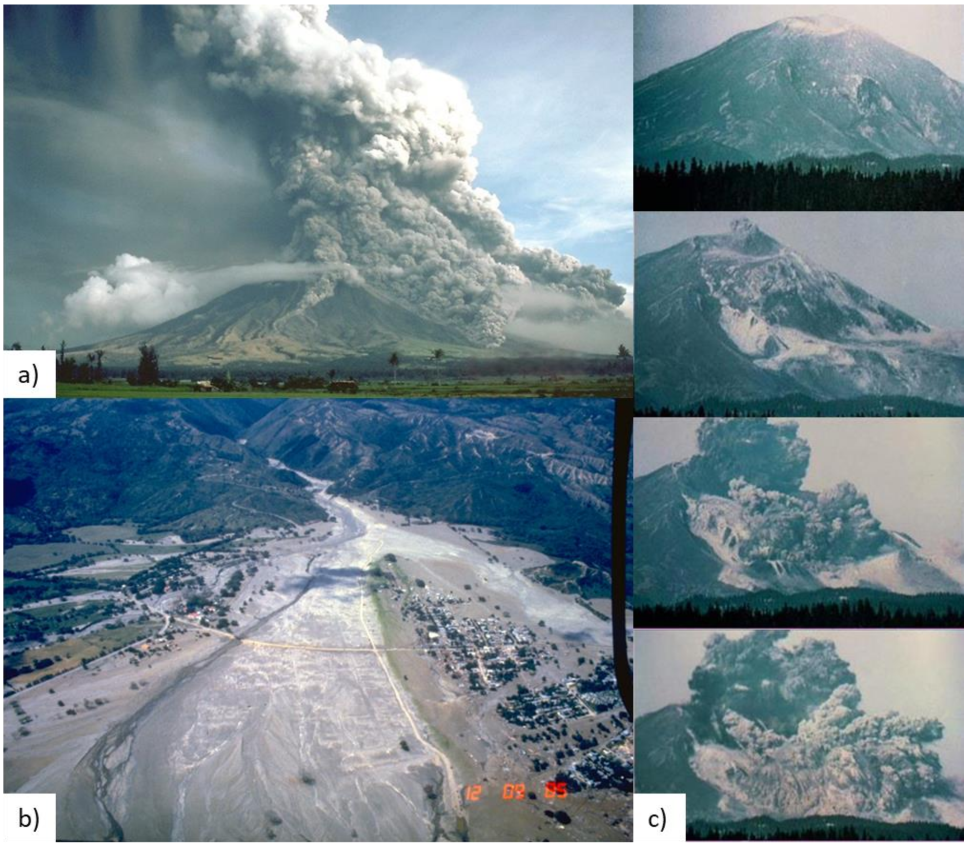


Figure 4. a) Pyroclastic flows from the Mayon volcano - Philippines Photo: C.G. Newhall. b) Lahars of the Nevado del Ruiz volcano – Colombia. c) Debris avalanche from Mount Saint Helens in 1980 - USA Photo: SkyAlert.

2.1.2. Volcanic hazards and maps

Hazard is defined as the probability that a place will be affected by a dangerous event (Linares et al. 2004). Regarding volcanic hazards, we refer to the potential physical threats due to the volcanic products that a volcano can expel when it erupts (Figure 2). For this reason, studying the geology and eruptive history of a volcano is an important factor when determining its hazard, being able to define its current state and predict its behaviour in the future.

Volcanic hazard maps are fundamental tools in the management and prevention of natural disasters. They cartographically delineate areas susceptible to being affected by one or more volcanic phenomena, such as lava flows, pyroclastic flows, ashfall, lahars, etc., previously identified as hazard-generating scenarios capable of causing damage to their surroundings (Macedo et al. 2017).

A hazard map represents the current situation, a natural reality in the face of volcanic hazards (Gutierrez et al. 2006), the map is divided into three zones: high hazard (red), moderate hazard (orange), and low hazard (yellow). The high and moderate hazard zones represent areas with the most frequent eruptions based on historical records. In contrast, the low hazard zones depict areas with potentially more explosive scenarios, which have been less common historically. The use of a hazard map is essential for preparation to the impact of a volcanic eruption in an area with active volcanoes. The map allows us to identify risk zones, enabling authorities and the population to make decisions regarding urban development, territorial planning, and the establishment of evacuation routes in case of emergencies (Figure 5). Hazard maps are dynamic and should be easy to interpret. They are typically valid until a new eruption occurs due to the changes in terrain that would happen during and after a major eruption. However, when eruptions are small, the changes are minimal, and consequently, the map remains valid (Gutierrez et al. 2006).

In recent years, there has been innovation in the development of hazard maps using probabilistic - deterministic tools and simulation software to prepare hazard maps, thus knowing which places may be affected. Mostly, this implies having a good geological mapping of the historical volcanic deposits, a cartographic base, and high-precision digital elevation models - DEM (at a centimetre scale). It also requires a good database about the volcanic system obtained through fieldwork and subsequent processing in the laboratory, along with the use of scenario simulation models to estimate the probability and areas of impact based on the emission of different volcanic products.

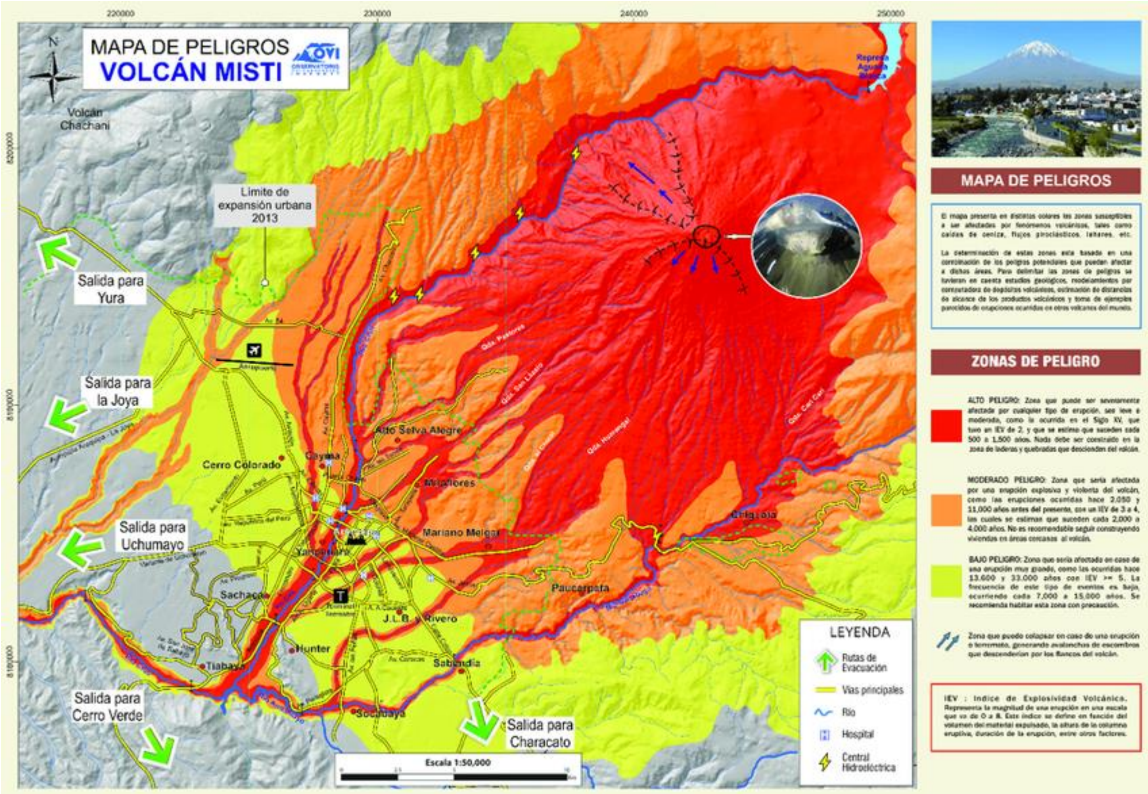


Figure 5. Hazard map of the Misti volcano in Peru, made by the geological survey of Peru, Instituto Geológico, Minero y Metalúrgico – INGEMMET (Mariño et al. 2007).

2.1.3. Volcanic risks and management

The concept of risk is complex, and involves several components (Cruz-Reyna et al. 2008). In the case of natural phenomena, such as volcanic activity, involves the expectation of adverse consequences for anthropogenic elements, such as population and infrastructure, which are exposed to hazards (Cruz-Reyna et al. 2008). On the contrary, in the absence of human presence or infrastructure, there is no risk (Linares et al. 2004). In summary, volcanic risk initially consists of two elements (Cruz-Reyna et al. 2008).

$$Risk = Hazard \times Vulnerability$$

The initial formulation of risk has been enriched over time, and research in risk management has suggested the inclusion of an additional component: exposure. Exposure refers to the value of assets susceptible to potential losses (Linares et al. 2004) or, according to Bonadonna et al. (2021), it involves the identification and quantification of assets in a specific area that could be affected by volcanic hazards, encompassing the natural system, built environment, social system, and economic system. This analysis is carried out using remote sensing techniques and satellite imagery (Corbane et al. 2017), with the aim of estimating tangible and intangible economic value (Bonadonna et al. 2021).

Additionally, the importance of considering the vulnerability factor from two perspectives has been recognized: physical vulnerability and systemic vulnerability. Physical vulnerability comprises specific criteria that examine the fragility of an element to a particular hazard, characterized by behavior depending on the level of hazard through fragility curve models (Zuccaro and Gregorio 2012). On the other hand, systemic vulnerability analyzes how urban and regional systems are capable of responding to physical damage caused by a hazardous event (Bonadonna et al. 2021). Thus, by incorporating this new factor, the risk formula now consists of three components (Linares et al. 2004).

$$Risk = Hazard \times Vulnerability \times Exposure$$

It is important to highlight those active volcanic zones are dynamic, with eruptive periods and periods of calm. Over the years, and with the advancement of science, many countries have developed and improved advanced tools, such as predictive models, monitoring instruments, emergency plans, and early warning systems for natural phenomena (Peppoloni 2023). These measures aim at reducing or mitigating the risk, how is the "preparation", "social capacity", or "resilience" that can be developed in these active volcanic localities (Cruz-Reyna et al. 2008; Van Wyk de Vries and Vereb 2019; Ajinder and Sushma 2012; Bonadonna et al. 2021; Van Niekerk 2011).

While the hazard is a phenomenon that cannot be avoided, its destructive effects can be minimized through timely actions (Peppoloni 2023) and advances in natural hazards. This involves preparing the population to understand the effects of volcanic hazards, developing emergency plans, conducting drills, providing safety equipment, and strengthening institutions responsible for risk management. In this way, societies can be better prepared to respond to the risk in an organized and coordinated manner, thus reducing human exposure threatened by these natural manifestations (Cruz-Reyna et al. 2008; Van Wyk de Vries and Vereb 2019).

The concept of resilience is a societal characteristic that signifies the ability to adapt to change and overcome challenges with minimal harm and maximum benefit. Unlike risk, which can be quantified into a formula as seen above, resilience is more nuanced and has not always been integrated into certain contexts. However, the conventional risk-vulnerability approach has demonstrated serious limitations, often overlooking societal dimensions and neglecting marginalized populations (van Wyk de Vries and Vereb 2019). Resilience begins with society itself, encompassing the needs, capacities, and cultural aspects of its people. It then considers various events that may impact them and aims to achieve the best possible outcomes within the natural environment, within the broader context of society (Lièvre et al. 2022).

According to this, the impact of preparation on risk reduction is reflected in a new parameter that defines each society's capacity to respond to reduce vulnerability. This results in a new simplified formula (Cruz-Reyna et al. 2008; Van Wyk de Vries and Vereb 2019; Ajinder and Sushma 2012; Van Niekerk 2011).

$$Risk = \frac{(\text{Hazard } \times \text{ Vulnerability})}{\text{Capacity of response or Resilience}}$$

Given the importance and level of detail required in the assessment and management of volcanic risk, Bonadonna et al. (2021) have proposed the ADVISE model (integrAteD VolcanIc risk asSEssment), which focuses on two temporal dimensions: short-term emergency and long-term risk management. This model serves as support for decision-making by authorities, considering the changing dynamics of the volcanic context. The ADVISE model offers a more robust formula that can provide more specific results by integrating hazard, exposure, vulnerability, and resilience for risk and emergency management in a volcanic context (Bonadonna et al. 2021).

2.2. Geodiversity and geoheritage

The use of the term geodiversity is increasingly common in scientific literature, originated as an analogue to the term biodiversity, which is the set of all living beings, the ecosystem, the environment in which they live and their relationship with each other. Although the use of the term "geodiversity" is relatively recent, it currently appears more and more frequently in articles and research related to geological heritage and geoconservation studies (Carcavilla et al. 2007). One of the most widespread texts dedicated to its development is by Gray (2013) who defines geodiversity as the natural range of diversity of geological (rocks, minerals and fossils), geomorphological (landforms and processes) and soil characteristics, including their relationships, properties, interpretations and systems.

While the term geoheritage is defined as the set of natural, non-renewable resources, whether rock formations, geological structures, sedimentary accumulations, landforms, or mineral, petrological or paleontological deposits, that allow us to recognize, study and interpret the evolution of the history of the Earth and the processes that have shaped it, with its corresponding scientific, cultural, educational, landscape or recreational value (Cendrero 1996; Gallego 1996). The set of this key places of geological interest or geosites are inventoried and characterized in a given region and well defined, with the occurrence of one or more elements of geodiversity with unique value of the scientific, educational, tourist, cultural or other point of view (Brilha 2005, 2018) and this must be valued and conserved for its content, being testimonies of the history of the Earth and with significant value (Pereira et al. 2006).

Currently, more specialized lines of study are being studied such as paleontological geoheritage, mining and archaeo-industrial geoheritage, geomorphological geoheritage, hydrogeological geoheritage (Carcavilla et al. 2007) and the most recent volcanic geoheritage in sites related to spectacular volcanic processes and deposits (Németh et al. 2017; Casadevall et al. 2019; Németh 2022; Dóniz-Páez and Pérez 2023).

2.3. Geotourism and geoconservation

The term geotourism appeared for the first time at the beginning of the 21st century, especially with the appearance and institutionalization of geoparks, which are areas with important geological heritage and rich natural and cultural environments (Zafeiropoulos et al. 2021). It is not only geological tourism, it is a broader concept, oriented to natural geological elements that highlight the value of a specific place, and minimize the cultural and environmental impact on the communities receiving important tourist flows and sustainable promotion strategy of a place, based on the dissemination of its geological heritage (Brilha 2005, 2018; Carcavilla et al. 2012; Santos and Brilha 2023). Geotourism also appeals to those interested in learning about the geological and geomorphological aspects of a place, with this being their main motivation for traveling (Moreira 2014). And it is an objective to raise awareness among tourists through interpretation strategies that enhance appreciation and learning of this heritage. This involves providing interpretation centers and geosites, promoting their sustainable use for conservation for future generations (Hose 2012; ASGMI 2018).

To achieve this, geotourism is based on the idea that the environment is made up of abiotic, biotic and cultural elements, an "ABC" Dowling (2013) approach, which includes the abiotic elements of geology and climate, the biotic (flora and fauna) and the cultural or human components of the past and present.

The term geoconservation was used since 1991, in Digne (France), as a result of previous meetings on this topic, with the proclamation of the International Declaration on the Rights of the Memory of the Earth (Schneider 2022), a couple of years later the European Association for the Conservation of Geological Heritage – ProGEO, which promotes the protection of geological places and landscapes of great value, as well as the diverse geological heritage of scientific, educational, tourist and cultural interest (www.progeo.ngo). Geoconservation is defined as the set of actions, techniques and measures aimed at ensuring the conservation and sustainable management of geological heritage, as well as natural and associated processes (Brilha 2005), based on the analysis of its intrinsic values, its vulnerability and the risk of degradation (ASGMI 2018), through inventories of points of geological interest worldwide (Carcavilla et al. 2007; Schneider 2022).

2.4. Benefits of volcanic activity as geosystem services and threats to conservation

Volcanism has provided benefits to human beings since prehistoric times, (Figures 6 and 7) its first uses were through the creation of utensils and weapons such as spearheads from mainly igneous rocks (intrusive and volcanic) and later from the metals contained in them. Today it is used in the production of specific components for technological devices such as cell phones, cameras, computers, vehicles, televisions. In the production of metallic mineral resources (such as gold, silver, copper, lead or zinc), precious and semi-precious stones used in jewellery. And non-metallic such as crushed basalt for paving roads and quarries for extracting construction materials such as cement and sand (Alvarado 2009).

One of the most important benefits that volcanism provides is the formation volcanic soils which are rich in elements such as iron, magnesium and potassium, so they produce very fertile soils and due to their porosity, they retain more moisture, being favorable for agricultural and livestock activities. Volcanism also allows us to obtain geothermal energy, that is, energy existing inside the earth in the form of heat, which is used to generate electricity and heating (Alvarado 2009).

Finally, another significant benefit is geotourism, which through nature protection and geoeducation, contributes to the development of responsible tourism, strengthens the local economy and sustainable development (Zafeiropoulos et al. 2021). With popular territories of national to international interest that attracts thousands of tourists every year.

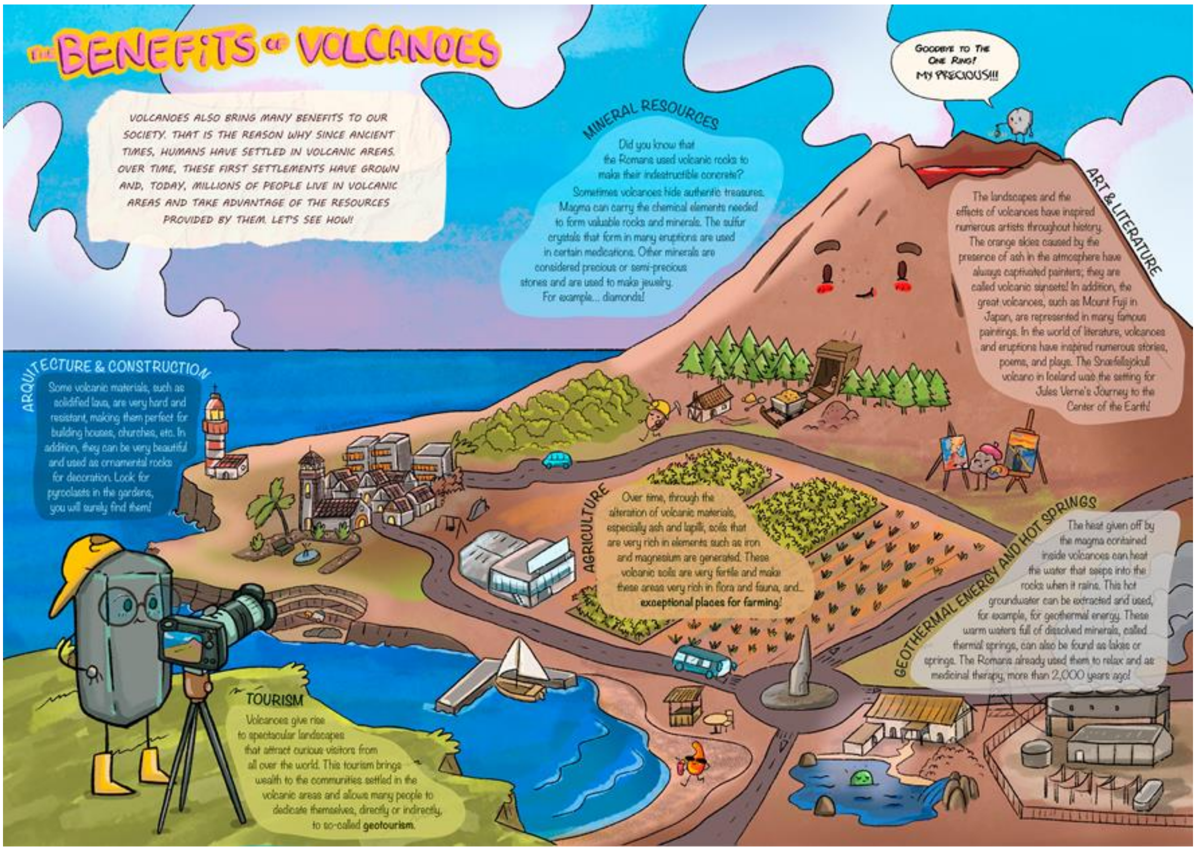


Figure 6. The benefits of volcanoes represented in a friendly way addressed to lay people and young people (Schamuells et al. 2023).

However, this heritage is delicate and susceptible to both natural and human-induced threats that can compromise its preservation (Figure 7). The fragility of these sites manifests in various ways, from the soft ground formed by recent volcanic eruptions to the vulnerable nature of silica or carbonate deposits in geothermal areas (Migoń and Pijet- Migoń 2016).

The risks to these sites intensify with increased visitation, reaching the point of overcrowding, which can lead to accelerated deterioration if daily carrying capacities are not managed (Migoń and Pijet- Migoń 2016; Santos and Brilha 2023). Urban expansion further exacerbates the degradation risk, especially when large populations reside in close proximity to these geosites. Additionally, natural soil erosion can result in the loss of key geological features over time.

Due to growing interest in geotourism, particularly towards volcanic landscapes and active volcanoes, the Commission on Volcano Geoheritage and Protected Volcanic Landscapes was established in 2015 as a part of the IAVCEI. This commission recognizes volcanic landscapes and regions as critical areas in need of protection and conservation (Showstack 2015; Németh et al. 2017; Németh 2022).

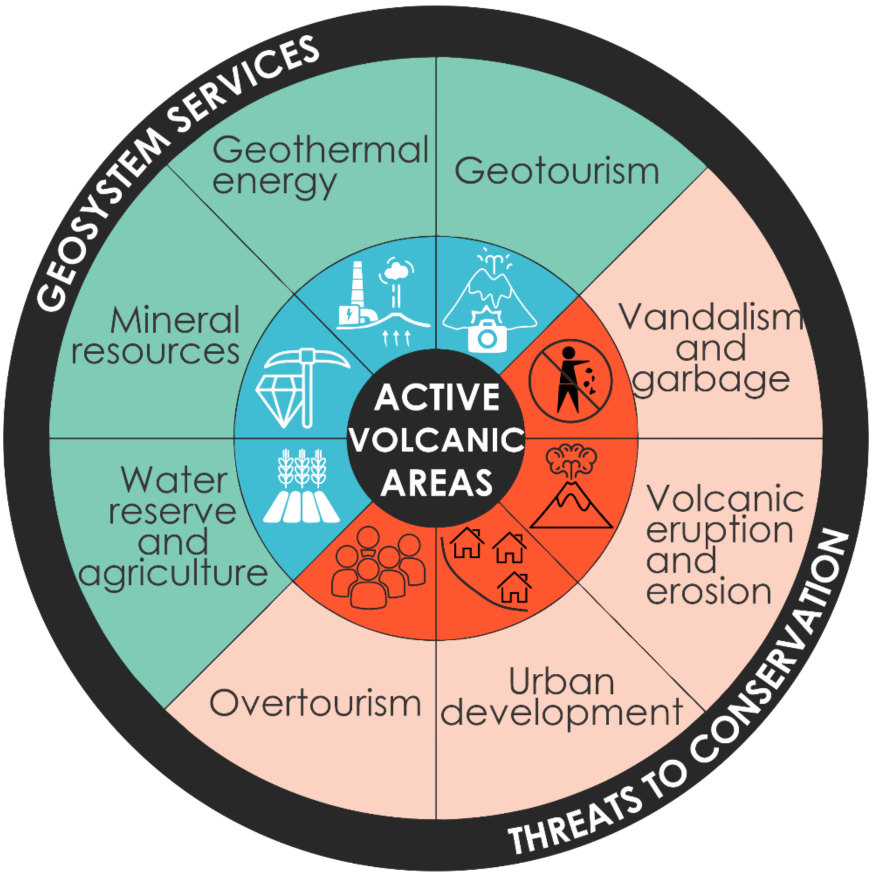


Figure 7. Geosystem services as the benefits of the volcanic areas to the society, and the threats to conservation in phase to the nature and anthropogenic factors.

2.5. Volcanic geoheritage

In recent years, there has been a notable increase in research focusing on geological heritage, particularly regarding sites of geological significance and their connection to Earth's history and processes (Németh et al. 2017). Geological heritage encompasses various elements of geodiversity, including a wide array of rocks, minerals, fossils, landforms, geographical features, geological and geomorphological units, structures, and geological-hydrological processes. However, the significance of these elements lies in their exceptional, representative, integral, scientific importance, and rarity (Brilha 2005). Efforts towards geoconservation aim to preserve these territories through actions and measures intended to safeguard the geological heritage for future generations (Gray 2013).

In this context, volcanic geoheritage showcases the captivating processes of volcanism, which pose risks to society but also provide numerous volcanic environments or "Geoenvironments" (Németh et al. 2017), for humanity. As noted by Erfurt-Cooper (2011), these environments offer a wide array of outdoor activities, providing opportunities for education about geoheritage and insights into their significant value for regional culture, religion, and history".

Due to these captivating characteristics, volcanic landscapes have caught the interest of many tourists and visitors worldwide. Consequently, geoheritage evaluation studies have been conducted, demonstrating their significant potential for use in geoeducation and geotourism (Joyce 2009, 2010a, b; Kazancı 2012; Migoń and Pijet- Migoń 2016; Alessio 2017; Sheth et al. 2017; Szakacs 2017; Szepesi et al. 2017). These methods are also utilized in disseminating information and facilitating geoscientific communication regarding volcanism, volcanic hazards, and risk management through geotourism.

2.5.1. Active volcanic regions with international designations

There are territories distinguished by their geological, biological, and cultural characteristics, among others, with primary objectives focused on nature conservation and fostering sustainable development in connection with local communities. Based on their geological significance and remarkable volcanic features, numerous sites have gained international recognition from various world organizations dedicated to promoting the preservation of these areas. Examples include the UNESCO Global Geoparks and UNESCO's World Heritage List, both of which aim to protect and promote these sites. A recent addition is the First 100 IUGS Geological Heritage Sites (Hilario et al. 2022), established by the International Union of Geological Sciences (IUGS), as key sites with geological elements and/or processes of international scientific relevance, used as reference, and/or with a substantial contribution to the development of geological sciences throughout history. This initiative acknowledges, promotes, disseminates, and educates about geological heritage sites worldwide.

The UNESCO Global Geoparks are geographical areas that utilize their geological heritage in conjunction with natural and cultural heritage to promote the sustainability of local communities, mitigate the effects of climate change, and reduce risks associated with natural hazards. These geoparks are founded on three fundamental pillars: education, geoconservation, and sustainable development through geotourism (UNESCO.org). Currently, there are 195 geoparks spanning 48 countries. Many of these geoparks boast geosites within their boundaries, showcasing deposits, formations, and landscapes sculpted by volcanic activity millions of years ago, including both historical and ongoing eruptions.

Among these geoparks, 28 host active volcanic activity and are renowned for the beauty of their volcanic landscapes (Figure 8). Some notable examples include Kütralkura Geopark (Chile); Arxan, Jingpohu, Leiqiong, and Wudalianchi Geoparks (China); Imbabura Geopark (Ecuador); Lesvos Geopark (Greece); Katla and Reykjanes Geoparks (Iceland); Batur, Gunung Sewu, Ijen, Merangin Jambi, Rinjani-Lombok, and Toba Caldera Geoparks (Indonesia); Aso, Hakusan Tedorigawa, Izu Peninsula, Oki Islands, Toya–Usu, and Unzen Volcanic Area Geoparks (Japan); Colca and Andagua Volcanoes Geoparks (Peru); Azores Geopark (Portugal); Jeju Island Geopark (Republic of Korea); El Hierro, Lanzarote, and Chinijo Islands Geoparks (Spain); Ngorongoro Lengai Geopark (Tanzania); and Kula-Salihli Geopark (Turkey).

Figure 8. Location of UNESCO Global Geoparks areas with active volcanism.

The World Heritage List aims to promote the identification, protection, and preservation of cultural and natural heritage worldwide, recognized for its "Outstanding Universal Value." This designation signifies that the heritage is so exceptional that it transcends national borders and holds common importance for present and future generations of humanity. To be included on the list, sites must meet at least one of the ten selection criteria outlined in the Operational Guidelines for the Implementation of the World Heritage Convention. The advisory bodies involved in the selection process include the International Union for Conservation of Nature (IUCN), the International Council on Monuments and Sites (ICOMOS), and the International Center for the Study of the Preservation and Restoration of Cultural Property (ICCROM). The criteria for inclusion in the World Geological Heritage list are defined by two main criteria: criterion (viii), which highlights sites as exceptional representatives of significant stages in Earth's history, encompassing the record of life, ongoing geological processes shaping landforms, and significant geomorphic or physiographic features; and criterion (vii), which applies to sites containing exceptional natural phenomena or areas of outstanding natural beauty and aesthetic importance (UNESCO World Heritage Centre 2023).

Currently, there are 1199 World Heritage Sites, many of which feature structures and landscapes formed by volcanic activity, including both historical and recent eruptions. Among these, 11 sites are inscribed under criterion (vii), and 9 sites under other criteria. Focusing specifically on active volcanic zones and criterion (viii), there are 16 registered sites (Figure 9), such as Heard and McDonald Islands (Australia), Virunga National Park (Democratic Republic of the Congo), Morne Trois Pitons National Park (Dominica), Galapagos Islands, Sangay National Park (Ecuador), Chaîne des Puys - Limagne fault, Volcanoes and Forests of Mount Pelée and the Pitons of Northern Martinique (France), Vatnajökull National Park - Dynamic Nature of Fire and Ice (Iceland), Isole Eolie, Mount Etna (Italy), Tongariro National Park (New Zealand), Jeju Volcanic Island and Lava Tubes (Republic of Korea), Volcanoes of Kamchatka (Russian Federation), Pitons Management Area (Saint Lucia), Teide National Park (Spain), and Hawaii Volcanoes National Park (United States of America).

Figure 9. Location of UNESCO World Heritage sites in areas with active volcanism.

Finally, IUGS has identified so far 21 geosites for their volcanic interest (Figure 10), such as the Quaternary Phlegrean Fields volcanic complex (Italy), the Holocene Puy-de-Dôme and Petit-Puy-de-Dôme volcanoes (France), Capelinhos volcano (Portugal), Taburiente volcanic caldera in La Palma Island (Spain), Danakil rift depression and its volcanism (Ethiopia and Eritrea), the Quaternary Cameroon Volcano (Cameroon), the historic scoria cone of the Jabal Qidr (Saudi Arabia), the Pleistocene Kilimanjaro Volcano (Tanzania), the Holocene Ulmen Maar (Germany), the 1905-1911 Matavanu volcanic eruption (Samoa), the active Yasur–Yenkahe volcanic complex (Vanuatu), Isla de Ometepe: Quaternary volcanoes in Lake Nicaragua (Nicaragua), Poás Volcano (Costa Rica), Nevado del Ruiz Quaternary Volcanic Complex (Colombia), Cotacachi - Cuicocha volcanic complex (Ecuador), the Quaternary Santorini Caldera (Greece), the vapor phase ignimbrites of Sillar in the Añashuayco Quarries of Arequipa, the Calicanto pyroclastic succession of the 1600 CE Huaynaputina eruption (Peru), the Miocene Cappadocian Ignimbrites sequence (Turkey), the Tatio geothermal field (Chile), and the Yellowstone volcanic and hydrothermal system (United States of America) (Hilario et al., 2022).

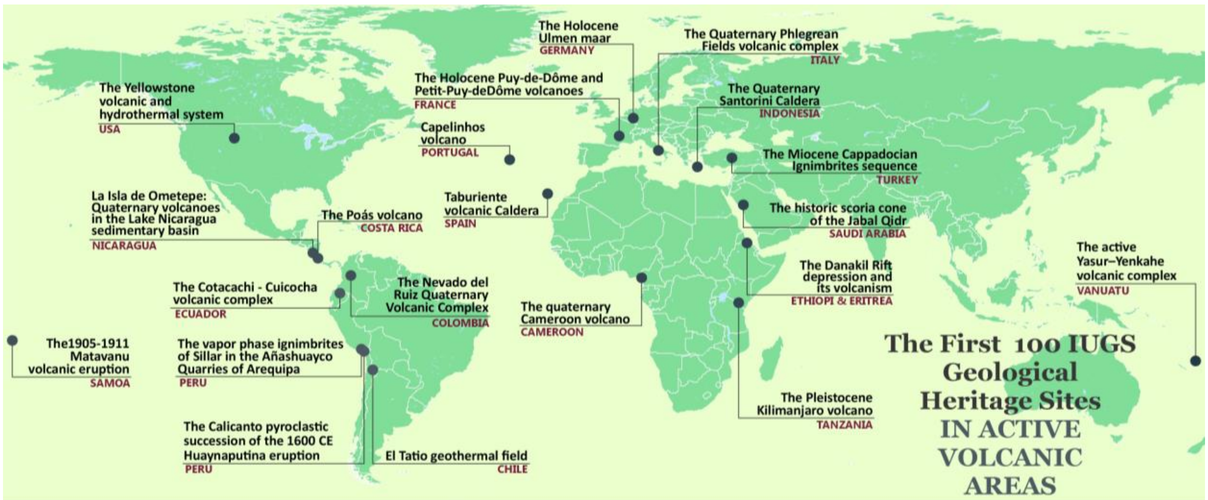


Figure 10. Location of the First 100 IUGS Geological Heritage Sites in areas with active volcanism.

2.6. Tourism in active volcanic areas

2.6.1. Background of geotourism in volcanic regions

As per Sigurdsson (1999), volcanic regions have progressively emerged as significant destinations for geotourism. People visit these areas for various reasons, such as seeing the natural environment of the volcano itself, personal motivations, developing different recreational activities or being attracted to being very close proximity to the awe-inspiring power of nature embodied in a volcano, that attract millions of tourists a year (Erfurt-Cooper 2014). While discussions about volcanoes typically center on their energy and mineral resources as beneficial aspects, it is imperative to recognize geotourism as another valuable resource stemming from volcanic activity.

Active volcanoes have attracted visitors since ancient times. In the 17th and 18th centuries, the aristocracy of northern Europe visited Vesuvius and Etna as part of the Grand Tour (Sigurdsson 1999). Currently, millions of people from around the globe visit volcanic regions each year for their landscapes, biodiversity, educational and adventurous opportunities, and the thrill of witnessing a volcanic eruption and molten lava first-hand. Examples include Kilauea in the USA, Stromboli in Italy, Fuego in Guatemala, Masaya in Nicaragua, and Eyjafjallajökull in Iceland. Some are drawn by the historical and archaeological significance, such as Vesuvius in Italy, Santorini in Greece, and Huaynaputina in Peru, while others visit for their ecological and social importance, found in national parks like Yellowstone or the national monument Mount St. Helens in the USA, biodiversity-rich volcanoes in El Salvador, Honduras, Guatemala, Costa Rica and Nicaragua, or the volcanic islands of the Galapagos in Ecuador. There are also volcanoes renowned for their stunning landscapes like the Canary Islands in Spain and Azores in Portugal, or those sought after for recreational activities such as skiing, like Osorno in Chile, Rainier in the US, and Cotopaxi in Ecuador. Finally, some volcanoes are admired purely for their beauty and symmetry, such as Mount Fuji in Japan, Mount Mayón in the Philippines, Mount Kilimanjaro in Tanzania, and Misti volcano in Peru.

The rise of geotourism has transitioned from being an exclusive activity favoured by the elite in the 18th century to a widely embraced form of travel today, with a notable surge in adventure tourism, geotourism, and ecotourism (Sigurdsson 1999; Erfurt-Cooper 2014). While volcanic tourist destinations like Vesuvius, Etna, Santorini, and Hawaii continue to attract thousands of visitors globally, lesser-known volcanoes now gaining more popularity, many examples are published in international indexed journals that denote their scientific interest (Erfurt-Cooper 2014; Casadevall et al. 2019; Dóniz-Páez and Pérez 2023). Such tourism, as it is interested in the place, can bring a more conscient, ethical class of tourism, in contrast to the mass tourism of beaches. This is an aspect becoming Important, as seen by the recent protests against mass tourism In the Canary Islands (BBC News 2024).

2.6.2. Examples of tourist casualties at popular volcanic sites

In certain volcanic regions, tourism managers and local authorities often implement measures to safeguard visitors. These measures may include establishing viewing areas situated at a safe distance from active areas, and offering of educational materials regarding volcanic risks. However, despite these precautions, accidents can still occur. In some cases, tourists may disregard safety warnings and venture too close to dangerous areas, leading to injuries or fatalities. In other cases, unexpected volcanic activity, such as sudden eruptions or volcanic gases, can pose risks to tourists.

When accidents occur in active volcanic areas, it is often a combination of different factors that contribute to the incident. This may include the behavior of tourists themselves, the effectiveness of safety measures implemented by tourism managers, and the unpredictability of volcanic activity. Ensuring the safety of tourists in active volcanic areas requires a combination of responsible behavior from visitors, and their guides, effective management and communication by tourism authorities, with a comprehensive understanding of the volcanic hazards. Presented below are various instances of human casualties occurring in prominent tourist destinations near active volcanoes are presented below. These cases illustrate the different factors that can lead to fatalities and underscore the importance of having an appropriate management plan in place.

2.6.2.1. Mount Saint Helens (USA, 1980)

The eruption of Mount Saint Helens, located in the state of Washington in the north-western United States, stands as one of the most catastrophic volcanic events of the 20th century, registering a Volcanic Explosivity Index (VEI) of 5. On the morning of May 18, 1980, at 8:00 am, a magnitude 5.1 earthquake triggered a massive "lateral blast" and the collapse of the volcano's entire northern flank, resulting in what is considered the largest landslide ever observed, directed toward Spirit Lake (Gondwana Talks 2020).

The emitted gases and pulverized volcanic material combined to form pyroclastic flows that rapidly descended the slopes with high velocity. The melting glaciers mixed with the pyroclastic material, generating deadly lahars, torrents of mud and sediment, that surged through river valleys at speeds ranging from 175 to 250 kilometres per hour, traveling a distance of 20 kilometres before reaching the

Columbia River (Francis and Oppenheimer 1993). In total, the eruption claimed the lives of 57 individuals, including tourists, locals, forest workers, and scientists, and caused significant physical damage.

2.6.2.2. Concepción and Maderas Volcanoes in Ometepe Island (Nicaragua, 2004)

Ometepe Island, located southwest of Nicaragua, lies in the heart of Lake Cocibolca. This island is home to the Concepción Volcano, which is active, and the Maderas Volcano, which is inactive. Renowned for its natural beauty, Ometepe Island is often hailed as a paradise destination and is highly favoured by both national and international tourists (La Nación 2004).

In November 2004, two tourists, went missing over two weeks after announcing their plan to climb Maderas volcano (without a guide). It appears they veered off the designated path and wandered into a steep, densely vegetated area, as the volcano's terrain features numerous deep ravines. Despite extensive search efforts led by brigades from the Nicaraguan police and army, along with volunteer North American mountaineers, only the bodies of the missing tourists were eventually discovered. Sadly, by the time they were found, their remains had been reduced to bones, having been consumed by scavenger birds (La Nación 2004). This incident marked the second occasion where foreign tourists vanished on the island. In October of the same year, the body of a young man from El Salvador, who had disappeared during an excursion to the Concepción volcano, was found.

2.6.2.3. Solfatara volcano (Italy, 2017)

The Solfatara volcano in the Campi Flegrei area, 20 kilometers west of Naples, has been attracting tourists for centuries. It has long been recognized by geologists for its volcanic activity and therapeutic mud baths (Scherer and Fenton 2017). The tragic incident occurred at Bocca Grande, the largest fumarole in the area, known to the ancient Romans as the abode of the god of fire. Emitting 160-degree Celsius water vapours and noxious gases, including hydrogen sulphide, the site poses significant hazards (Scherer and Fenton 2017).

An Italian couple and their 11-year-old son succumbed to asphyxiation and extreme temperatures. Firefighters on the scene reported that the victims were vacationing. Eyewitnesses recounted that the boy crossed a fence barring access to the perilous area of the crater, inadvertently falling into the most volatile section emitting toxic vapours and hot mud. His parents rushed to his aid but tragically fell into the crevice alongside him, resulting in their demise (Scherer and Fenton 2017).

2.6.2.4. Stromboli volcano (Italy, 2019)

The Stromboli volcano is located on a small island bearing the same name in the Tyrrhenian Sea, forming part of a volcanic archipelago north of Sicily. The most recent violent eruption was recorded in June 1932, lasting until February 1934 (Venzke 2023; Barberi et al. 1993). Since then, its ongoing eruptions have been continuously monitored due to its permanent surveillance. Stromboli is not only a popular vacation spot but also attracts millionaires and celebrities, earning its designation as a UNESCO World Heritage Site (https://whc.unesco.org/es/list/908).

In July 2019, a significant eruption occurred, characterized by a violent paroxysmal explosive sequence, which, despite the volcano's regular explosive activity, is considered rare by the National Institute of Geophysics and Volcanology of Italy (Baynes 2019). Tragically, a tourist died while ascending towards the volcano's summit, reportedly due to the descent of ballistic projectiles, as stated by a rescue service official. Another tourist was injured, causing others to jump into the sea, while approximately 500 residents of the town of Ginostra stayed in their homes for safety. Witnesses described hearing a deafening roar and witnessing the explosion from nearby hotels, as ash clouds blanketed the sky, leaving everyone in shock (Baynes 2019).

2.6.2.5. Whakaari or White Island (New Zealand, 2019)

Whakaari/White Island has been New Zealand's most active volcano since 1976, located 48 km offshore, is a popular tourist destination, with tours departing from the town of Whakatane. The island constitutes the summit of a vast underwater volcano, with approximately 70% of its structure submerged beneath the ocean's surface, while rising about 300 meters above sea level. Characterized by a wide crater opening towards the southeast, it features steep crater walls and an active Main Crater area situated at the rear of the crater floor, towards the northwest (Smithsonian Institution 2020). Despite being privately owned, the Institute of Geological and Nuclear Sciences Limited (GNS Science) researchers and the group of Geophysical Networks – GeoNet, conducts continuous monitoring of volcanic activity through remote surveillance and periodic visits to the volcano (www.gns.cri.nz).

In 2018, approximately 17,500 people visited the island. Tragically, ten lives were lost in 1914 when a section of the crater wall collapsed, impacting sulphur miners. More recently, on 9 December 2019, a brief explosion occurred, resulting in an ash plume and pyroclastic surge that affected the entire crater area. At the time of the eruption, there were 47 tourists on the island, unfortunately, 22 of them died, and many others were injured. (Smithsonian Institution 2020; Sharma 2020).

A criminal case was initiated, in which WorkSafe, which regulates incidents in New Zealand, investigated the eruption, determining that despite being an unexpected event, it does not mean that it was unforeseeable and tour operators have a duty to protect those under their care. Since scientists from GNS had raised the alert level to 2 as "moderate to intense volcanic unrest," four weeks before the eruption occurred (Sharma 2020; Clark 2023). The brothers who own Whakaari, through their company Whakaari Management Limited (WML), are accused in this case, as well as the tour companies ID Tours New Zealand and Tauranga Tourism Services. Another defendant was GNS Science, but in their defense, it was indicated that they have no relationship with the owners and tour operators of Whakaari, and that legally they are not obliged to provide advice to these agencies. WML could request a quantitative risk assessment regarding trips to the volcano, which had an additional fee, but they decided not to pay (Sharma 2020; Clark 2023).

2.6.2.6. Klyuchevskaya Sopka volcano (Russia, 2022)

The Klyuchevskaya Sopka volcano, located in eastern Russia, holds the distinction of being the most active volcano in Eurasia. Tragically, nine out of twelve climbers, comprising ten tourists and two guides, lost their lives while attempting to ascend the volcano. Only three climbers (two tourists and one guide), were successfully rescued by helicopter and transported to the nearest villages in Klyuchi. The unfortunate demise of the remaining nine climbers was reported by local media (Van Brugen 2022). The three survivors were among those who remained at the campsite. One of them suffered from frostbite on his extremities, while the other two escaped unharmed. According to local reports, the group of twelve initially camped at an altitude of 3,300 m.a.s.l, but nine members decide to ascend further. Tragically, five of them fell, while the others succumbed to hypothermia. Rescuers highlighted those temperatures on Klyuchevskaya Sopka can plummet to -14 degrees Celsius during the night, making the rescue operation extremely complicated, in addition due ash clouds from volcanic eruptions, the debris flows and rockfalls (Van Brugen 2022).

The volcano is located between the Sea of Okhotsk to the west and the Pacific Ocean and the Bering Sea to the east. It is part of the UNESCO World Heritage-listed natural volcanoes of Kamchatka and has erupted more than 50 times since 1700. Following the incident, the Russian Investigative Committee initiated a criminal complaint for "Causing death by negligence of two or more people," as reported by the Russian News Agency - RIA Novosti (Van Brugen 2022). As a result of this incident, the director of the "Extreme Time" agency was sentenced to 4 years in prison for the deaths of the tourists. The court determined that the agency's services failed to meet the necessary safety standards, for the life and health of consumers and led to the death of more than two people due to negligence. It was highlighted that the guides lacked proper training and did not possess the required qualifications to organize the trip. The verdict was handed down by the Municipal Court of Petropavlovsk-Kamchatsky (Annapurna 2023; Skylis 2023).

2.6.2.7. Merapi volcano (Indonesia, 2023)

Mount Merapi, a highly active stratovolcano located on the border between the provinces of Central Java and the Special Region of Yogyakarta, Indonesia, recently erupted on December 3, 2023. The eruption tragically resulted in the loss of 22 climbers out of a total of 75, all of whom were Indonesian nationals present in the area at the time of the event (Gipuzkoa 2023). While some climbers were successfully evacuated and returned home, the injured were transferred to local hospitals. Unfortunately, the deaths of those who were missing were confirmed in the days following the eruption.

The eruption occurred around 14:54 on Sunday, as reported by the Center for Volcanology and Geological Disaster Mitigation (PVMBG). Mount Merapi had been at alert level three (on a scale of four) since Friday, leading up to the explosion on Sunday. Residents of nearby towns captured the eruption on video and shared it on social media platforms, showing the massive pyroclastic column expelled by the volcano, which caused ash rain down in the area (Euronews 2023). Subsequently, the national disaster management agency (BNPB) continued to closely monitor the volcano to quickly respond and manage the evacuation of residents in case of any further significant volcanic activity (Euronews 2023).

2.6.2.8. Misti volcano (Peru, 2024)

The Misti volcano, an active volcano near Arequipa city in southern Peru is designated as a UNESCO World Heritage site and attracts a substantial number of national and international tourists annually. Many visitors, either independently or with the assistance of tour guides, opt to explore the area, including ascending the volcano and visiting other sites of geological interest.

Currently, the Misti volcano is not erupting, with only small fumaroles, making ascending to the crater a popular adventure tourism activity in Arequipa. On the February 23, 2024, a group of six tourists and two guides set out to climb the volcano after midnight. Upon reaching the summit, the guides decided to begin the descent (Exitosa Noticias 2024). A Chilean tourist lost his life during the descent when he fell into a 400-meter-deep quebrada, resulting in instant death. Despite warnings from the guides, reports indicate that the tourist did not heed the recommendations regarding the unstable surface he was traversing (Exitosa Noticias 2024). Separating from the group, he slipped and fell despite efforts by the guides to prevent the accident. The steep and slippery terrain, exacerbated by rain and snow, prevented the guides from reaching him, leading to fatal injuries upon impact with the rocks (El Búho 2024).

2.6.3. Examples of tourism management

2.6.3.1. Costa Rica – Turrialba Volcano National Park

The Ministry of Environment and Energy of Costa Rica, through the conservation area, developed a management plan for the Turrialba Volcano National Park, with the objective of promoting the conservation and protection of natural and cultural resources. The Park also has a contingency plan prepared by the national commission for risk prevention and emergency response. This document presents the volcanic risk scenarios, presenting possible scenarios for unforeseen situations, reported and extreme situations. According to information and communication from the Volcanological and Seismological Observatory of Costa Rica and the National Seismological Network UCR-ICE. Resources have been identified in the contingency plan for the immediate response to a dangerous event, taking into account the personnel who are permanently and uninterrupted in the national park. After the implementation of such a plan, it must be constantly monitored and periodically updated to take into account natural and societal changes (Salazar et al. 2012).

2.6.3.2. New Zealand – Geothermal sites of the Taupo volcanic zone

The geothermal sites from Taupo to the Rotorua area provide examples of good practice in the development of geothermal tourism in New Zealand, these sites are popular in the region with approximately one million visits per year (Migoń and Pijet- Migoń 2016). In this area, protection measures have been adopted mainly in terms of physical facilities, with good planning and monitoring in which it is evaluated that the geological heritage may be threatened, as well as the safety of visitors.

According to Migoń and Pijet-Migoń (2016) the control and security measures implemented at the most popular sites are not too intrusive or negatively interfere with the scenic qualities of the geology. For tourist visits, there is flexibility and comfort in the tours that can be self-guided. Tourist flow management measures have been implemented in the sites in terms of physical facilities, such as security measures, schedules and entry control, designated paths of paved roads or wooden walkways and stairs in more critical places and warning signs in the busiest areas. As safety measures for tourists, there are warning signs about areas of hot ground and the hazards of collapse, there are also natural limitations of vegetation which prevent tourists from passing through (Migoń and Pijet-Migoń, 2016).

2.6.3.3. United States of America - Hawaii Volcanoes National Park

The management plan for Hawaii Volcanoes National Park was developed collaboratively by the Hawaii Emergency Management Agency and the state of Hawaii. It comprises distinct sections delineated by zones, taking into account both natural and cultural resources. Within the park, there is also an emergency operations plan addressing many natural hazards, fires, and a disaster recovery plan.

The management and protection measures are implemented to ensure visitor safety and safeguard the park's resources. The primary hazards affecting the area, in terms of frequency, include hurricanes, flash floods, tsunamis, earthquakes, volcanic eruptions and others. In the case of volcanic risk, it is recommended to remain vigilant about monitoring activity, information which is also provided at information centers. Areas of the park with significant volcanic gas emissions, such as "Crater Rim Drive," may be temporarily closed for safety in case of increased activity and reopened once levels decrease. The infrastructure and evacuation plans are well-planned, with emergency routes and trained personnel at visitor centers providing information to tourists. The plan also Include a topic about commercial services, transportation, guides, and visitor safety during tours.

The Park offers educational programs and materials to help visitors understand volcanic hazards and how to stay safe while exploring the park. It also facilitates on-site research for scientists. Overall, the management of Hawaii Volcanoes National Park takes a proactive approach to volcanic risk, working diligently to ensure visitor safety and preserve the park's natural and cultural resources in the face of volcanic activity. (Hawaii National Park Service 2016; Hawaii emergency management agency 2017).

2.6.3.4. France - Chaîne des Puys - Limagne fault tectonic arena

The management plan for the preservation and sustainable development of the Chaîne des Puys and the Limagne fault aims to provide a practical and accessible framework across three main axes (Conseil général du Puy-de-Dôme 2019). Firstly, it prioritizes the maintenance of the physical integrity and visual coherence of the volcanic landscape while enhancing its aesthetic qualities. Secondly, it emphasizes the responsible management of tourism activities to ensure a high-quality visitor experience that aligns with the property's values and supports local economic growth. Finally, it seeks to foster knowledge sharing and research, empowering local residents to actively participate in the territory's evolution and enhancing the site's international recognition through scientific endeavors.

The plan introduces protective measures for the value of the Chaîne des Puys and the Limagne fault, including the preservation of the structural geology model, conservation of the iconic monogenetic volcano field, maintenance of the harmonious landscape with remarkable aesthetics, enhancement of the site's scientific and educational significance, and harmonization of international promotion with sustainable local development efforts (Conseil général du Puy-de-Dôme 2019).

2.6.3.5. France - Volcanoes and Forests of Mount Pelée and the Pitons of Northern Martinique

The management plan for the Volcanoes and Forests of Mount Pelée and the Pitons of Northern Martinique is built upon the intricate connection between Martinique's inhabitants and the island's natural beauty and rich cultural heritage (Coisy et al. 2021). The broader framework is aimed at safeguarding and enhancing distant views of the property, occasionally facilitating public reception and awareness, and serving as a conduit to the property, whether adjacent to the buffer zone or not (including viewpoints, strategically located visitor centers, among others).

The development of the property's management plan involved extensive consultations with stakeholders and civil society, guided by the values inherent to the territory to preserve its Outstanding Universal Value (OUV). Now serving as a roadmap for the next six years, the plan has been validated by all partners and stakeholders in the region. Governance is structured according to the areas to be managed, with key strategic axes framing management actions. Axis 1 focuses on preserving the property's OUV, while Axis 2 emphasizes enhancing and exchanging knowledge about biodiversity and geodiversity. Axis 3 involves scientific dissemination and mobilization of cultural values and human history to engage the population in OUV issues, preservation, and territorial projects. Axis 4 is dedicated to the territorial project, utilizing the buffer zone as a space for project and development initiatives, including structural development and implementing a tourism action plan. Lastly, Axis 5 underscores the significance of international cooperation in achieving the management objectives (Coisy et al. 2021).

2.6.3.6. Iceland - Vatnajökull National Park – Dynamic Nature of Fire and Ice

The management plan for Vatnajökull National Park takes into consideration the evolution of tourism, nature conservation, and administration (Vatnajökull National Park 2013). It outlines the objectives for conservation within the park, focusing on five main goals: the protection of natural and cultural heritage, the establishment of guidelines for public access and operations, the provision of services including transportation, research, education, and information dissemination, the implementation of policies supporting employment, communities, and economic development in nearby areas. Conservation efforts encompass the assessment of both natural and cultural heritage values. Land use planning include the designation of protected areas across different regions of the park, including the Northern, Eastern, Southern, and Western regions, as well as specific wilderness areas. Moreover, infrastructure such as service areas and utilities are strategically positioned to meet visitor needs while minimizing environmental impact. Integral to the plan are monitoring and research programs, which inform ongoing management decisions and ensure the sustainability of the park's resources.

Furthermore, the plan aims to reflect the expectations and joint plans of stakeholders involved in various efforts, outdoor activities, or otherwise engaged within the operational area of the National Park.

Its objectives are set to enable Park Directors and other public bodies to achieve their roles effectively, supporting other stakeholders in their efforts for the benefit of the National Park and surrounding areas through actions, management, and procedures (Vatnajökull National Park 2013).

2.6.3.7. Korea - Jeju Volcanic Island and Lava Tubes

The Management Plan for Jeju Island Geopark serves as a blueprint for overseeing, regulating, and preserving nine designated geosites, which are central to the Geopark's identity. It addresses management issues such as mitigating agricultural influences on the underground ecosystem and effectively handling the influx of visitors to the area. Additionally, it outlines the prospect of expanding the Geopark to encompass additional noteworthy lava tube systems and volcanic attributes across Jeju Island (Cultural Heritage Administration Republic of Korea 2008).

The plan supports protection of the geosites, the promotion of geotourism, and the sustainable economic growth of the Jeju Island Geopark. It is structured around three primary components. Firstly, it proposes establishing a comprehensive management structure to ensure sustainable and coordinated management of geosites within the Geopark, aligning with other natural, cultural, social, and economic considerations (Cultural Heritage Administration Republic of Korea 2008). Secondly, it emphasizes implementing site management and monitoring strategies to protect and enhance the natural and cultural values of the geosites, ensuring their preservation for both current and future generations. Lastly, the plan aims to forge linkages and systems that promote collaboration among education, tourism, and research sectors. This collaborative effort seeks to deepen understanding of geological heritage while simultaneously contributing to the advancement of Jeju's economy and social well-being (Woo et al. 2013).

The current plan considers legal aspects of protection and management, potential pressures on the geosites, current management practices and facilities. It also considers future plans regarding the establishment of a regional identity for Jeju Island Geopark, the promotion of the geosites improving attractions, access, tourism support infrastructure, and visitor accommodation. The plan also outlines the location and function of interpretation centers, designation of tourist routes, and areas requiring significant signage. It emphasizes developing partnerships, involving the community and non-governmental organizations, establishing a code of ethics for visitors and researchers, training managers and guides, promoting research, and always with the constant monitoring (Woo et al. 2013).

2.6.3.8. Spain - Teide National Park

The land comprising Teide National Park is owned by the state, municipalities, and private entities (Arnay et al. 2006). The general management criteria are related to the conservation of natural and cultural resources, public use and visitor attention, research and monitoring of resources, traditional uses and exploitation, infrastructure, equipment, and facilities, the park's relationship with its surroundings and with administrative coordination guidelines, staff image, and qualification.

The management plan for the park encompasses several key objectives: safeguarding the landscape and native biodiversity, preserving archaeological sites and cultural values, fostering ecological stability and diversity, supporting scientific research and monitoring volcanic activity, balancing public enjoyment with conservation goals, promoting environmental education and awareness, stimulating socio-economic development in local communities, ensuring compatibility among objectives, maximizing synergy among activities for park and island benefit, contributing to Spain's National Parks Network as a representative of volcanic processes and ecosystems, and participating in international nature conservation programs to uphold global heritage preservation efforts (Arnay et al. 2006).

The management plan proposes the delineation of zoning to balance the protection of the Park with its public use while minimizing potential negative impacts. The Park's territory is spatially divided into Reserve Zones, Restricted Use Zones, Moderate Use Zones, and Special Use Zones based on their capacity to accommodate visitors. It includes legal regulations for the protection, utilization, and use of the territory, a proposal for infrastructure and facilities to enhance visitor experience, along with an economic estimation of the corresponding investments. All of these aspects are managed by an administrative organization (Arnay et al. 2006).

2.6.3.9. Ecuador - Galápagos Islands

The management plan for Galápagos is structured around four overarching objectives divided into six thematic programs, viewing Galápagos as a socio-system that should transition towards an integrated spatial planning model, bridging the gap between conservation and development (Parque Nacional Galápagos 2021). The objectives are to preserve Galápagos ecosystems and their insular and marine biodiversity to sustain ecological services; to integrate Galápagos conservation into territorial planning for sustainable development, promoting rational use of ecological services and biodiversity; to enhance the management capabilities of the National Park Service (PNB) for effective and efficient management; and to improve participatory and inclusive social processes to promote well-being (Parque Nacional Galápagos 2021).

The current management plan for Galápagos adopts an adaptive management approach, incorporating regular monitoring and internal evaluations. This allows the park to adapt its management strategies based on evolving knowledge, closely coordinated with the Galápagos Governing Council. The plan is organized around assessment areas, introducing decision-making alternatives to address specific management gaps. It focuses on enhancing capacities (human, technical, and financial) and improving coordination among institutions to address the potential and imminent threats. These threats include maintaining biodiversity and the integrity of the property, controlling invasive species, managing tourism development, and regulating fishing activities (Parque Nacional Galápagos 2021).

III. ASSESSMENT METHODOLOGY FOR GEOSITES IN ACTIVE VOLCANIC AREAS

For the proper management of geosites in active volcanic zones, it is essential to establish a robust inventory of these sites and, based on the findings, develop a comprehensive management plan. This chapter presents an enhanced proposal for assessing geosites, drawing inspiration from various previous approaches and incorporating improvements that can be applied and adapted to projects in regions with active volcanism. The objective is to facilitate the development and implementation of management plans that effectively address volcanic risk while promoting safe geotourism practices.

To ensure a systematic assessment, it is essential to establish a methodological sequence organized into two primary stages (Table 1, 11):

(1) The inventory of geological sites, integrates qualitative criteria, drawing inspiration from the pioneering proposals of Cendrero (1996); Brilha (2005); and Pereira et al. (2007). Subsequent adaptations of these methodologies by Martínez (2010); Zavala et al. (2016); Arias (2021) and Mariño et al. (2021) have contributed to its evolution and enhancement.

(2) The numerical assessment of the scientific value, educational and touristic use, and degradation risk using quantitative criteria will directly follow the methodology proposed by Brilha (2016). Additionally, the numerical assessment of visitor risk is incorporated, to evaluate the hazards and vulnerabilities that tourists face regarding volcanic activity at each geosite. These results will be essential for developing an effective management plan and ensuring safe geotourism experience.

Table 1. Geosite assessment and management plan, stages and sub-stages (Arias 2021; modified structure from Pereira et al. 2007).

STAGE		SUB-STAGES
GEOSITE ASSESSMENT IN ACTIVE VOLCANIC AREAS	Inventory of geological sites	Identification of potential sites
		Fieldwork and selection of geosites
		Qualitative assessment and characterization
	Numerical assessment	Scientific use
		Educational use
		Touristic use
		Geosite risk
		Visitor risk

3.1. Inventory of geological sites

The geosite inventory represents the initial descriptive phase of the valuation process. It involves compiling a record of sites with geological significance, providing general information about potential geosites within a specified study area. The duration and scope of this inventory phase depend not only on the area under study but also on the quantity and diversity of geosites present. This stage serves as a filter process by which a “Potential geosite” is considered as a “Geosite”. It covers three substages: Identification of potential geosites, selection of geosites, and qualitative assessment and characterization (adapted from Pereira et al. 2007).

3.1.1. Identification of potential sites

The identification of potential geosites of significant geological importance is conducted through fieldwork, focusing on key locations where the geological significance is evident. Each site is documented with basic information and accurately mapped out, accompanied by a field description. These sites are cataloged in a table with essential information such as the geosite name, coordinates, altitude, primary geological features, general characteristics, and any available bibliographic references.

3.1.2. Fieldwork and selection of geosites

This substage, is as a preliminary assessment of potential geosites, requires more time in areas with numerous proposed sites (depending on each framework). It is crucial to maintain objectivity and select the most suitable options, particularly concerning this main characteristic.

- Representativeness: Ability of a geosite to illustrate geological elements or processes (Brilha 2005, 2016).
- Integrity: State of conservation of the main geological elements (Brilha 2005, 2016).
- Rarity: Number of similar occurrences in an analyzed area (Brilha 2005, 2016).
- Scientific knowledge: The existence of published scientific studies on the geosite (Brilha 2005, 2016). But for new or recently discovered geosites, consider their potential for scientific research.

- Aesthetic: Highlights aspects such as spectacularity or beauty, scenic and aesthetic qualities, taking into account the visual uniqueness of geomorphological elements, panoramic quality, diversity of elements and the presence of vegetation and water (ASGMI 2018; Brilha 2005).

- Didactic: Ability to show representative geological processes (Brilha 2005).

- Safety: It is related to tourist security, which is the protection of life, health, physical, psychological and economic integrity of tourists, service providers and members of the receiving communities (Grunewald 2010).

- Visibility: It refers, if the selected site has obstacles, in the terrain or vegetation that covers the different geological features (Pereira et al. 2007).

- Accessibility: Considers the degree of difficulty of the access roads to the geosite, taking into account main roads, trails, parking lots and distances to be travelled on foot (Pereira et al. 2006).

Based on these criteria and through fieldwork, we can select the geosites using a dynamic chart (Figure 11). The geosites with high value and low vulnerability to hazards and limitations are marked in green and are selected first. The geosites in orange are those to be considered in a future evaluation if the limitations can be overcome or if measures can be taken to mitigate the hazards. Finally, the geosites in red have many limitations and high hazards, and they may also have a low value, so they are not considered. With the final list of selected geosites, we can proceed to the next stage of detailed characterization of each geosite.

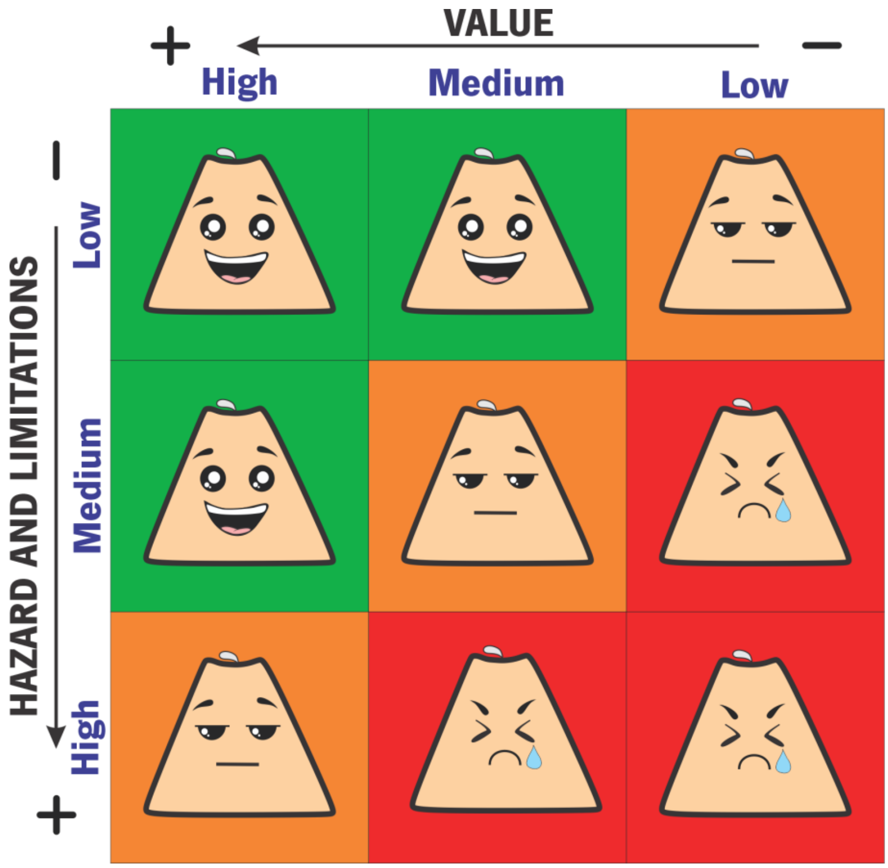


Figure 11. Graphical representation using geomojis of the selection of geosites, according to the value criteria already mentioned and the existence of hazard or limitations (Shires and Van Wyk de Vries 2024).

3.1.3. Qualitative assessment and characterization

The qualitative assessment and characterization of potential geosites will be carried out using tables with specific information for each geosite (adapted from Arias 2021, and based on proposals by Pereira et al. 2007, and Zavala et al. 2016). Each table will present essential data for individual geosites, covering general attributes, potential use and need for protection. Furthermore, a section can be included for observations and photographs of the geosite (Table 2). These tables are flexible and can be adjusted based on evaluator criteria, as each geosite, influenced by its location, possesses unique characteristics distinct from others. In each case, evaluators must assess the value of each geosite, categorizing it as very low, low, medium, high, or very high.

General values

- Scientific knowledge: The richness of elements, encompassing diverse geological processes, alongside the potential for conducting highly significant research, characterizes the site. (Brilha 2005).
- Didactic: The geosite can demonstrate many different types of geological processes. (Brilha 2005).
- Recreational: The potential for recreational activities, alongside the presence of other natural or cultural attractions, makes it easy for non-experts to observe and understand its geological features (ASGMI 2018). Explore additional aspects beyond economic benefits, such as quality, personal attention, and social recognition, which contribute positively to the tourist experience (Solís 2016).
- Ecological: The connection and interaction between the selected location and its natural surroundings are crucial during this preliminary phase (Pereira et al. 2007).
- Cultural: The geosite holds cultural heritage in the form of significant monuments that embody the history, prehistory, architecture, or culture of the region and nation. It also encompasses preserved works of art and artifacts from ancient civilizations, representing a valuable cultural legacy.
- Aesthetic: This emphasizes elements with magnificence, beauty, and aesthetic appeal, considering the visual distinction of geomorphological features, panoramic views, diversity of elements, and the presence of vegetation and water bodies. (ASGMI 2018; Brilha 2005).
- Rarity: The number of similar occurrences in the study area (Brilha 2005).

Potential use

- Zone/ current activity: Consider whether the geosite is situated in a rural area, distant from populated regions, within an urban setting, part of an industrial/mining zone, an established tourist destination, or none of these categories.
- Safety: Related to tourist security, encompassing the safeguarding of the life, health, physical, psychological, and economic well-being of visitors, service providers, and members of the host communities (Grunewald 2010).

- Administrative situation: The geographical context of the geosite is specified, indicating whether it is under state ownership, private ownership, municipal ownership, designated as a protected area, or its ownership status is unknown.
- Influence at level: The significance of the geosite is evaluated based on its importance at the local, regional, national, or international level according to the evaluator's criteria.
- Obstacles to use: Determines if there are any barriers or obstacles that make it difficult to propose and establish it as a geosite.

Conservation state and vulnerability

- Degree of deterioration: This metric quantifies the extent of damage and loss of integrity suffered by the geological elements within the geosite.
- Visibility: This criterion assesses whether the chosen location is obstructed by terrain features or vegetation that obscure the various geological features (Pereira et al. 2007).
- Protection: This refers to having security measures in place to safeguard the well-being of the geosite.
- Protection urgency: The urgency to protect geosites is determined by assessing their level of vulnerability.
- Hazard to the geosite: Identify the potential risks posed by natural or anthropogenic hazards that the geosite faces.
- Hazard to the tourist: Describe whether the geosite poses a risk to tourists. Specify the nature of the hazard, whether it can be mitigated with safety structures, or if it requires inclusion in an emergency plan.
- Location on the volcanic hazard map: This criterion determines If the geosite is situated within any hazardous zones outlined on the hazard map associated with the associated volcano.

Table 2. Qualitative assessment and characterization table, that will be used for all geosites (modified from Arias 2021 and Pereira et al. 2007).

QUALITATIVE ASSESSMENT AND CHARACTERIZATION					
Geosite name				Code:	
Description:				Confidentiality of information:	Publish
					Restricted
					Confidential
LOCATION AND ACCESSIBILITY					
Country:	Region:	Province:	District:	Place:	
Coordinates	Latitude	Longitude	East	North	Zone:
					Altitude:
Accessibility	Very difficult	Difficult	Moderate	Easy	Very easy
Distance (m/km)	Paved road	Unpaved road	Dirt road	Nearest city	Distance
Road state	Bad	Regular	Good		
GEOLOGY					
Type	Igneous (intrusive)	Igneous (volcanic)	Hydrothermal	Volcanic landscape	Others
Volcanic deposit or structure:	Pyroclastic flow	Pyroclast fall	Lava flow	Lava tubes	Debris avalanche
	Lahar	Crater/caldera	Lava dome	Slag cone	Hot springs
Group		Formation		Geological age	
GENERAL VALUES					
Scientific knowledge	Very low	Low	Medium	High	Very high
Didactic	Very low	Low	Medium	High	Very high
Recreational	Very low	Low	Medium	High	Very high
Ecological	Very low	Low	Medium	High	Very high
Cultural	Very low	Low	Medium	High	Very high
Aesthetic	Very low	Low	Medium	High	Very high
Rarity	Very low	Low	Medium	High	Very high
POTENTIAL USE					
Zone/Current activity	Rural	Urban	Industrial/ Miner	Tourism	None
Safety	Very low	Low	Medium	High	Very high
Administrative status	State ownership	Private property	Mixed	Protected area	Unknown
Influence level	Local	Regional	National	International	
Obstacles to use it	Yes	No	Specify		
CONSERVATION STATE AND VULNERABILITY					
Degree of deterioration	Low	Medium	Advanced		
Visibility	Low	Medium	High		
Protection	Deficient	Insufficient	Enough		
Protection urgency	Urgent	Medium term	Long term		
Hazard to the geosite	Flood	Low	Medium	High	
	Landslide	Low	Medium	High	
	Volcanic eruption	Low	Medium	High	
	Graffiti/vandalism	Low	Medium	High	
	Erosion	Low	Medium	High	
Hazard to the tourist	Yes	No	Specify		
Location on the volcanic hazard map:		Low (Yellow)	Moderate (Orange)	High (Red)	
ADDITIONAL COMMENTS:					
LOCATION MAP AND GEOSITE BOUNDARIES:					

3.2. Numerical assessment

The second stage aims to quantitatively evaluate geosites to understand their main potential uses in scientific, educational, and touristic aspects. This is important for determining the type of management each site requires. Additionally, it is important to assess whether the geosite is vulnerable to degradation and implement measures that do not impact the site negatively due to geotourism. Finally, a quantitative analysis and evaluation of the risk posed to tourists by natural phenomena, especially volcanic hazards and associated risks such as geothermal and meteorological hazards, are conducted to ensure safe geotourism.

3.2.1. Quantitative assessment of scientific, educational, and touristic uses and geosite risk

For effective management of geological heritage in geosites, it is imperative to understand the diverse potential of each site independently. Not all geosites can be visually attractive to everyone, as each possesses unique characteristics that attract attention for different purposes based on tourists' interests. Therefore, Brilha (2016) developed a methodology with quantitative criteria to evaluate and classify geosites according to their scientific value (SV), potential educational use (PEU), potential touristic use (PTU), and degradation risk (DR). This assessment must be objective, ensuring that once the criteria are numerically evaluated, the final value of each site can be determined, considering the evaluator's judgment. For this research, for the clarity and objectivity of the criteria, it is proposed to include this evaluation method in this "Geosite assessment methodology in active volcanic areas" simplifying the terms to scientific use, educational use, touristic use, and geosite risk, respectively. The latter refers to natural or anthropogenic impacts that may directly affect the natural state of the geosite. Finally, these results will help propose better management strategies for geosites and significant geoconservation strategies since many volcanic sites are highly vulnerable to deterioration due to their recent deposition and lack of consolidation.

Table 3. Criteria and weightings for the assessment of scientific, educational, and touristic uses and geosite risk (modified from Brilha 2016).

SCIENTIFIC USE	**SU**	**EDUCATIONAL AND TOURISTIC USES**	**EU**	**TU**
Criteria	**Weight (%)**	**Criteria**	**Weight (%)**	
A. Representativeness	30	A. Vulnerability	10	10
B. Key locality	20	B. Accessibility	10	10
C. Scientific knowledge	5	C. Use limitations	5	5
D. Integrity	15	D. Security	10	10
E. Geological diversity	5	E. Logistics	5	5
F. Rarity	15	F. Density of population	5	5
G. Use limitations	10	G. Association with other values	5	5
		H. Scenery	5	5
GEOSITE RISK	**GR**	I. Uniqueness	5	5
Criteria	**Weight (%)**	J. Observation conditions	10	10
A. Deterioration of geological elements	35	K. Didactic potential	20	-
B. Proximity to areas / activities with potential to cause degradation	20	L. Geological diversity	10	-
C. Legal protection	20	K. Interpretative potential	-	10
D. Accessibility	15	L. Economic level	-	5
E. Density of population	10	M. Proximity of recreational areas	-	5

Table 4. Geosite risk classification (modified from Brilha 2016).

TOTAL WEIGHTED	**GEOSITE RISK**
<200	Low
201 - 300	Moderate
301 - 400	High

To classify geosites based on their significance and primary utility for scientific, educational, and tourism purposes, the interpretation of results from the previous evaluation will be utilized. This will involve developing a ranking that establishes the hierarchy of geosites according to the weighted values assigned to different criteria (Table 3), indicating that certain criteria carry more weight than others. Additionally, the main potential of each geosite will be compared to determine its primary utility. Regarding the results of geosite risk, it will be determined if it is low, moderate or high level (Table 4).

3.2.2. Quantitative assessment of visitor risk

At this stage, new guidelines are proposed to assess the current condition of the geosite and determine if it poses any hazard to visitors based on the volcanic current activity and understand how to act in the event of an increase in the premonitory signs or a volcanic eruption.

To start the process, it is important to have a solid bibliographic base and knowledge about the territory's geodiversity, including comprehensive fieldwork. Subsequently, it is essential to identify within the working area any volcanic or geothermal activities, meteorological conditions, or other hazard factors. These serve as vital background information regarding potential hazards arising from natural phenomena that could pose risks to visitors or infrastructure.

Regarding volcanic activity, it is important to identify the types of volcanoes in the area and their eruptive history. This helps us understand what kind of eruption could happen in the future. We also need to know if the volcano is currently active, dormant, extinct, or if there are any active fault lines or monogenetic fields nearby. A simple way to assess risk areas is by using volcanic hazard maps or risk maps. These maps show us the probability of different areas being affected by an eruption based on different volcanic scenarios, helping us understand the different types of hazards involved. If there is no hazard map available or if it is still being made, it is important to consult geologists - volcanologists, to use geological maps of volcanic deposits, stratigraphy columns, etc. and the distances to geosites to estimate potentially risky areas. This information can be verified with support from geological surveys.

In the ideal scenario of having a volcanic hazard map or risk map, geosites should be located on these maps to identify if they are on high-risk, moderate-risk, low-risk, or no-risk zones (Figure 12). Additionally, more criteria to conduct quantitative assessments objectively to determine their status and level of safety under normal circumstances when the volcano is calm (green), when its activity increases (orange), or when it erupts (red) as the volcanic alert light (Figure 12, Table 10).

All the criteria to consider are divided into two blocks, such as "human factor" (1 to 8), those that depend on the work carried out by the human team, and "natural factor" (9 to 12), which depend on the volcano and meteorological conditions. For each criterion, the evaluator will assign a score ranging from 1 to 4 (Table 5).

1. **Hazard map:** Assess the availability of a volcanic hazard map, whether it exists, is currently being prepared, or if there are plans for its development in the future.
2. **Geosite location in the hazard map:** Determine if the geosite is within the boundaries delineated on the volcano's hazard maps, and specify its location within those designated areas. If there is no hazard map, estimate hazard zones according to the location of volcanic deposits in the geological map or taking into account the records of recent eruptions.
3. **Current monitoring:** Assess whether the volcano is currently under monitoring by any public or private organization, employing multidisciplinary monitoring techniques such as seismic, geodetic, visual, chemical, remote sensing, etc. Determine if this monitoring is conducted in real-time or on an intermittent basis.
4. **Access routes:** Take into account the proximity to the nearest well-maintained access routes, which serve as valuable evacuation routes in case of emergency.
5. **Safety and evacuation:** Evaluate the difficulty associated with evacuating visitors from the site, taking into consideration the presence of safe zones, shelters, signage, or maps delineating evacuation routes.
6. **Current use of the geosite and/or future projection:** Assess the frequency of visits and current utilization of the geosite, as well as its projected future potential for tourist, educational, and scientific purposes.
7. **Control of visits to the geosites:** Evaluate if there is control of tourists who visit the geosites or georoutes through a central office, park rangers or guides, in this way having knowledge and control of the number of visitors in case of emergency.
8. **Number of inhabitants in the closest population:** Identify the population size of the nearest settlement within different distance radii. Recognize that higher population densities indicate increased vulnerability in the event of a volcanic eruption.
9. **Potential hazard:** Assess the potential hazards that may occur at the site by referencing the geological map of deposits from past eruptions and the corresponding hazard map, focusing on the most common scenario, typically associated with low hazard levels.
10. **Volcanic alert level - Orange:** Assess the status of the geosite following a change in the volcanic alert light from green to orange (Figure 12, Table 10). Based on hazard maps, geological data, and bibliographic sources, determine whether the geosite remains safe for tourists or requires restrictions.

11. **Volcanic alert level - Red:** Assess the status of the geosite following a change in the volcanic alert light from orange to red (Figure 12, Table 10). Based on hazard maps, geological data, and bibliographic sources, determine whether the geosite remains safe for tourists or requires restrictions.
12. **Potential meteorological and other hazards:** Assess the status of the geosite in response to potential weather phenomena such as hurricane-force winds, rainfall, or storms that may cause lahars, floods, or potential hazards such as rockfalls, landslides, increased geothermal activity. Based on this assessment, determine whether the geosite remains safe for tourists or requires restrictions.

Table 5. Criteria for the assessment of visitor risk.

	CRITERIA	SCORES	INDICATORS
	1. Hazard Map	1	There is an updated hazard map.
		2	No hazard map but it is being done.
		4	No hazard map.
	2. Geosite located in the area of the hazard map (Distance)	1	Site located in the Yellow Zone - low hazard.
		2	Site located in the Orange Zone - moderate hazard.
		4	Site located in the Red Zone - high hazard.
	3. Current Monitoring	1	Full real-time monitoring.
		2	Partial real time or intermittent monitoring.
		4	No monitoring.
	4. Access Routes	1	Site located less than 500 m from a well-maintained road.
		2	Site located less than 1 km from a road in good condition.
		4	Site located more than 1km from a road in good condition.
	5. Safety and Evacuation	1	Evacuating to safe areas or temporary shelters is facilitated by the presence of maps and signage indicating evacuation routes.
		2	Evacuating to safe areas or temporary shelters is feasible, although there is a lack of maps or signage providing guidance on evacuation routes.
		4	Evacuating to safe areas or temporary shelters presents difficulties. Or there is an absence of maps or signs indicating evacuation routes.
HUMAN FACTOR	**6. Current use of the geosite and/or future projection**	1	The geosite is rarely visited, usually only for scientific purposes.
		2	The geosite receives a moderate number of visitors, mainly for tourism and/or educational activities; visitation tends to rise.
		4	The geosite is highly popular for both tourist and educational activities.

	7. Control of visits to geosites	1	The geosite does not need control or a central office and park rangers are in place to regulate the number of tourists visiting the geosite/ georoutes.
		2	There is a future plan to implement visitor control measures at the geosite or along sections of a georoute, utilizing a central office, park rangers, or guides to manage and regulate tourist numbers.
		4	There is currently no visitor control mechanism in place, nor is there a future plan to regulate the number of tourists visiting the geosite or sections of any georoutes.
	8. Number of inhabitants in the area	1	Less than 500 thousand within a 10 km radius.
		2	Between 500 thousand to 1 million within a 15 km radius.
		4	More than 1 million inhabitants within a 20 km radius.
NATURAL FACTOR	**9. Potential volcanic hazard**	1	Fine ashfall, gases.
		2	Ashfall and lapilli, pyroclastic flows, debris avalanche, active lahars, hot springs, gases.
		4	Ashfall, lapilli, ballistic projectiles, pyroclastic flows, gases, debris avalanche, lava flow, active lahars, hot springs.
	10. Volcanic alert level: Orange	1	Safe geosite, open for visits without restrictions.
		2	Geosite that may be on alert, allowing visits with limited capacity. However, staying informed is essential.
		4	Geosite with potential restrictions in case of an orange alert volcanic scenario.
	11. Volcanic alert level: Red	1	Safe geosite, open for visits without restrictions.
		2	Geosite that may be on alert, allowing visits with limited capacity. However, staying informed is essential.
		4	Geosite with potential restrictions in case of a red alert volcanic scenario.
	12. Potential meteorological and other hazards	1	Safe geosite, open for visits without restrictions.
		2	Geosite that may be on alert due to frequent rains, which can cause lahars and rockfalls due to strong winds. It can still be visited with limited capacity.
		4	Geosite can be restricted during a meteorological event of great intensity such as heavy storms, hurricane-force winds, floods, and lahars, or is a site susceptible to landslides, active faults, and strong geothermal activity.

After assessing the visitor risk (Table 5), we will utilize weighted scores (Table 6) to obtain the final score based on criteria 9, 10, 11, and 12, as the main ones influenced by increased volcanic activity, potential volcanic hazards, meteorological factors, and others.

Table 6. Criteria weights for the assessment of visitor risk.

	VISITOR RISK CRITERIA	WEIGHT
HUMAN FACTOR	1. Hazard Map	5
	2. Geosite located in the area of the hazard map (Distance)	5
	3. Current Monitoring	5
	4. Access Routes	5
	5. Safety and Evacuation	5
	6. Current use of the geosite and/or future projection	5
	7. Control of visits to geosites	5
	8. Number of inhabitants in the area	5
NATURAL FACTOR	9. Potential volcanic hazard	15
	10. Volcanic alert level: Orange	15
	11. Volcanic alert level: Red	15
	12. Meteorological events and other hazards	15
	TOTAL	100

Subsequently, considering the results and the range of the total score (Table 7), we can conclude that during periods of active volcanoes in calm or normal state, marked as green (Figure 12, Table 7), all geosites are considered safe for visitors. However, if volcanic monitoring instruments detect precursory signals and an orange volcanic alert (Figure 12, Table 7, 11) is issued, geosites scoring above 201 are classified as being on alert. In such cases, it is recommended to stay informed about possible restrictions on daily carrying capacity.

Finally, in the event of a red volcanic alert (Figure 12, Table 7), geosites scoring between 301 and 400 are immediately restricted, those scoring between 201 and 300 remain on alert, and those scoring below 200 are considered safe under all circumstances. However, human judgment of the specialist must be considered in the final decision.

Table 7. Visitor risk classification for geosites.

TOTAL WEIGHTED	VISITOR RISK
<200	Secure geosite
201 - 300	Geosite to be on alert if the volcanic alert light changes to orange
301 - 400	Geosite to be restricted if the volcanic alert light changes to red

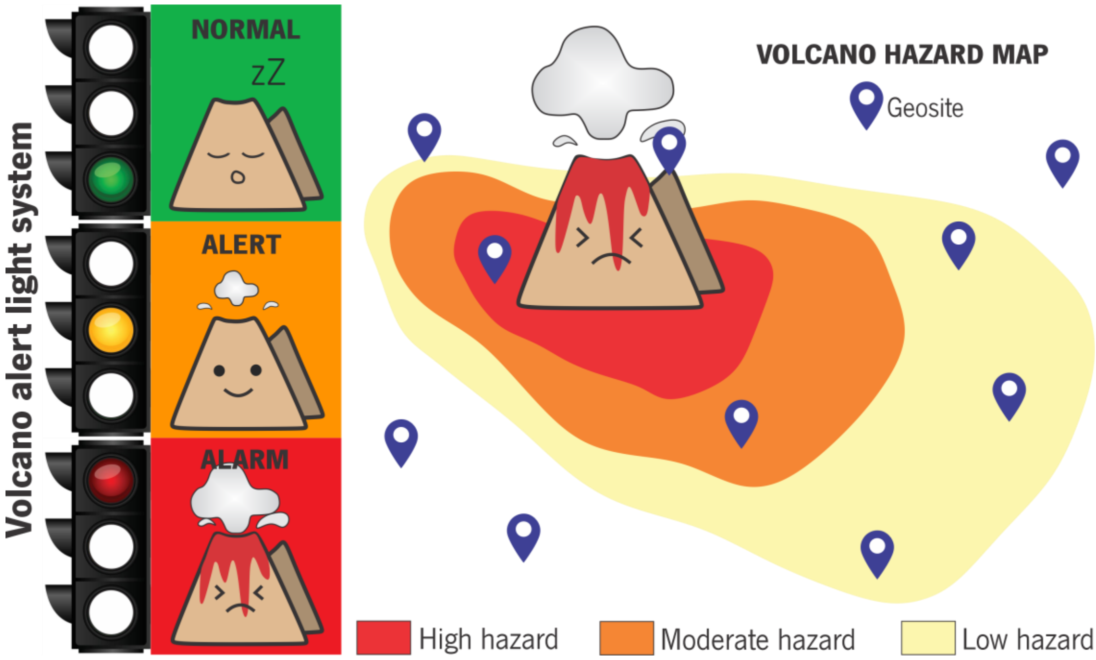


Figure 12. Volcano alert light system and volcano hazard map to considerate in the interpretation of results of the geosite's status using geomojis (Shires and Van Wyk de Vries 2024).

3.3. Application of the proposed visitor risk assessment

3.3.1. Arequipa, Peru

The geosites of Arequipa in southern Peru are primarily of volcanic interest and are associated with deposits and structures from the past activity of the Misti (active), Chachani (dormant), and Yura monogenetic volcanic field. So far, 12 geosites have been inventoried (Figure 13) (Arias et al. 2021).

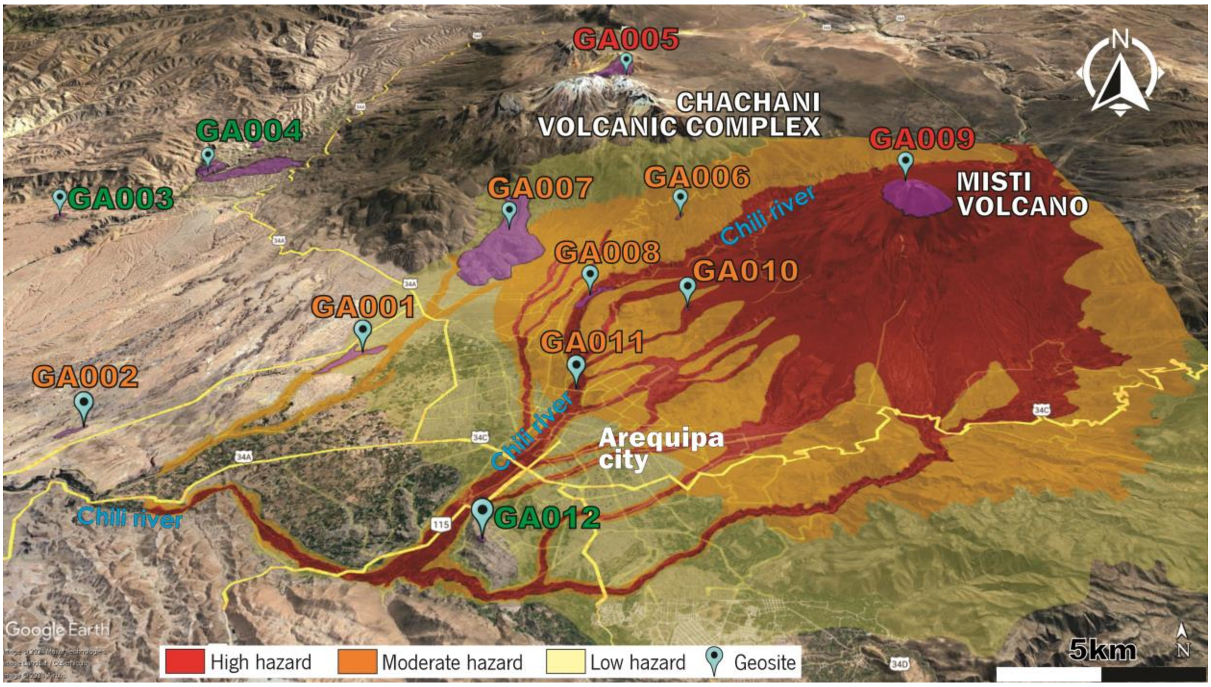


Figure 13. Location of geosites in Arequipa, on the hazard map of the Misti volcano. Añashuayco Sillar Route (GA001), Ignimbrites from "quebrada Culebrillas" (GA002), Nicholson monogenetic volcano (GA003), Ccapua, Yura viejo, Uyupampa monogenetic volcanoes (GA004), Colorful volcano and Volcancillo dome (GA005), Rainbow pyroclasts of Misti (GA006), Chachani lavas (GA007), Ignimbrites from Río Chili canyon (GA008), El Misti crater (GA009), A mix of volcanic deposits from Misti and Chachani (GA010), Magnopata Historic Lahars (GA011) and Arequipa 360° view from Kasapatac (GA012), (Hazard map taken from Mariño et al. 2007).

Table 8. Simulation of the "Visitor risk" assessment of geosites in Arequipa.

Criteria	**GA 001**	**GA 002**	**GA 003**	**GA 004**	**GA 005**	**GA 006**	**GA 007**	**GA 008**	**GA 009**	**GA 010**	**GA 011**	**GA 012**
1	5	5	5	5	5	5	5	5	5	5	5	5
2	20	10	0	5	20	10	10	20	20	20	20	0
3	5	5	5	5	5	5	5	5	5	5	5	5
4	5	5	10	5	20	5	10	5	20	10	5	5
5	5	5	5	5	20	5	10	5	20	10	5	5
6	20	20	5	5	10	10	5	20	20	5	5	10
7	5	5	5	5	20	10	5	20	20	10	10	5
8	10	10	10	10	10	10	10	10	10	10	10	10
9	30	30	0	0	60	30	30	60	60	60	30	0
10	30	30	15	15	60	30	30	30	60	30	15	15
11	60	60	15	30	60	60	60	60	60	60	60	15
12	60	60	15	15	60	30	30	60	60	60	60	15
TOTAL	255	245	90	105	350	210	210	300	360	285	230	90

Considering that Misti volcano and Chachani volcano are currently exhibiting normal and calm activities (Figure 12), we can conclude that all geosites are safe for visit, whether for educational, scientific, or recreational purposes.

However, in the event that the volcano shows premonitory signs of activity and moves to an orange alert status (Table 7, 8), the geosites that scored higher than 201 will be considered geosites in an alert state (GA001, GA002, GA005, GA006, GA007, GA008, GA009, GA011 and GA010). Finally, if the activity increases and moves to a red alert status (Figure 12, Table 7, 8), the first geosites to become restricted sites are those that scored higher than 301 (GA005 and GA009 are affected, while GA001, GA002, GA006, GA007, GA008, GA011 and GA010 remain in an alert state), always considering the final decision from volcanologists.

These results are compatible with the empirical knowledge of the area. During an eruption event, geosites GA005, located on the upper slopes of the Chachani volcano, and GA009, the crater of Misti, clearly represent sites of higher hazard. Geosites highlighted in orange, located further away from the volcanoes, may still be visited but require prior information regarding specific use restrictions or changes in carrying capacity. Geosites marked in green, on the other hand, are more distant and hence are safer locations during an emergency. Nevertheless, it is imperative that volcanologists validate and make the final decision based on these results, in case any specific geosite requires different considerations.

3.3.2. Ometepe Island, Nicaragua

The geosites of Ometepe Island in Lake Cocibolca, Nicaragua is primarily of volcanic interest and are associated with the past activity of the Concepción (active) and Maderas (dormant) volcanoes (Figure 14). Currently, there is a proposal for 10 geosites that will be tested for the "Visitor Risk" evaluation.

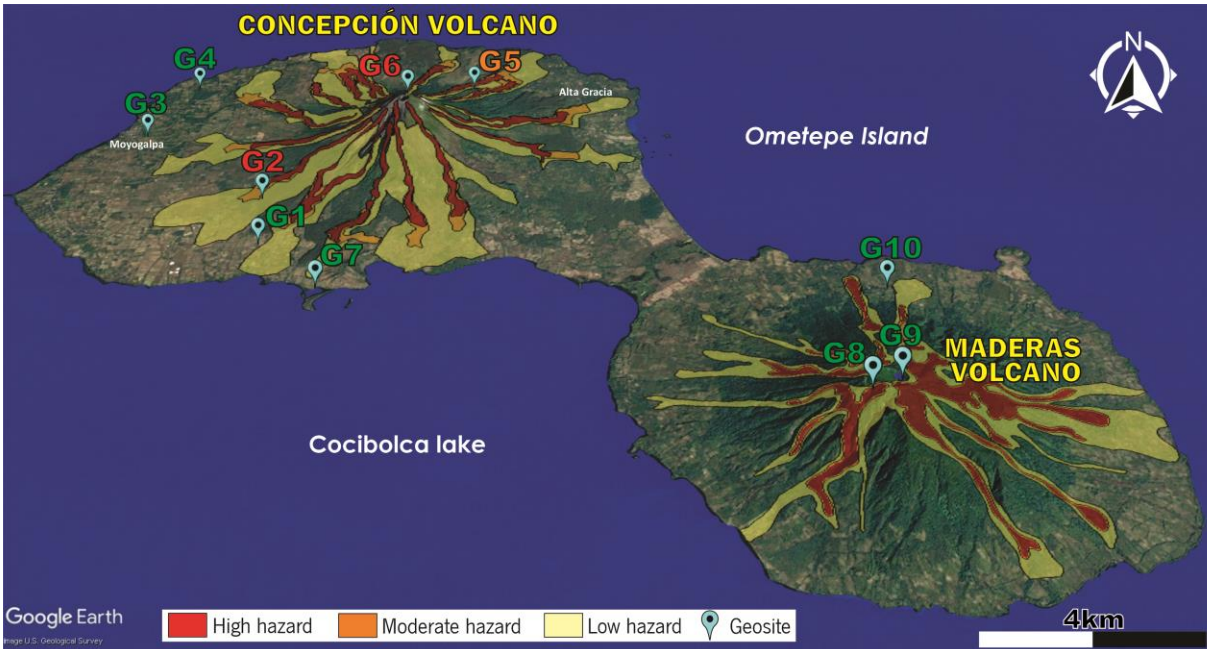


Figure 14. Location of geosites in Ometepe island, on the hazard map of the Concepción volcano. Pyroclastic deposits of San José del Sur (G1), Historic lahars of San José del Sur (G2), Pyroclastic deposits of Lomas de Moyogalpa (G3), Lacustrine sediments and lava flows of Tierra Blanca (G4), Pul lava flow 1957 (G5), Crater of Concepción volcano (G6), Charco Verde Lagoon (G7), San Ramón Waterfall (G8), Crater of Maderas volcano (G9), and Lavas and petroglyphs of Maderas volcano (G10), (Hazard map taken from ineter.gob.ni).

Table 9. Simulation of the "Visitor risk" assessment of geosites in Ometepe.

Criteria	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10
1	5	5	5	5	5	5	5	5	5	5
2	10	20	5	0	10	20	5	10	5	0
3	10	10	10	10	10	10	10	10	10	10
4	5	20	5	5	10	20	5	20	20	5
5	5	10	5	5	10	20	5	20	20	5
6	10	10	10	5	10	20	20	20	20	20
7	5	20	5	5	10	10	5	5	5	5
8	5	5	5	5	5	5	5	5	5	5
9	15	60	15	15	30	60	15	15	15	15
10	15	60	15	15	30	60	15	15	15	15
11	30	60	30	15	60	60	15	15	15	15
12	15	60	30	15	30	60	15	60	60	30
TOTAL	130	340	140	100	220	350	120	200	195	130

According to the results, it is important to note that the Concepción volcano is active, while the Maderas volcano is dormant but poses risks of lahars during the rainy season. However, under normal conditions, we can confidently state that all geosites are safe, in terms of georisk (visitors could still have accidents, though).

If the Concepción volcano shows premonitory signs and escalates to an orange alert level, geosites G2, G5, and G6 would enter into a state of alert with potential restrictions, following prior information dissemination (Figure 12, Table 7, 9). Should the alert level escalate to red, geosites G2 and G6 would be immediately restricted, while G5 would remain on alert (Table 7, 9). The safety of other geosites is maintained, although the final decision must be made by specialists, and these results may be reconsidered.

Comparing the results with real-life scenarios, they logically identify the most exposed areas, with the crater designated for immediate restriction in the event of an eruption. Other sites are placed on alert, while those farther away are considered safe, always subject to the specialists' final decision, depending on the eruption's intensity. These results can serve as a reference guide.

IV. MANAGEMENT PLAN FOR GEOSITES IN ACTIVE VOLCANIC AREAS

It is essential that every geoheritage site aiming for active development in geotourism, geo-education, and geoscientific activities has a comprehensive management plan, which is an essential tool to guide the administration, maintenance, and protection of a territory. This plan should outline clear objectives, provide structure, and articulate a vision and mission that guide the site's operations in an orderly and sustainable way. Such management plans are vital for conserving the key characteristics of geoheritage over the medium-long term.

But at the same time there are areas vulnerable to geological hazards such as volcanic activity, so the management plan is a tool in making decisions aimed at safeguarding the safety of visitors. Therefore, the plan also includes integrating volcanic risk mitigation measures and a contingency plan for visitors in the event of a volcanic eruption, which may restrict access to dangerous areas and install warning systems when necessary. The manual "Management Planning Natural World Heritage Properties" (IUCN Protected Areas Programme 2008) emphasizes the importance of addressing key issues in World Heritage management plans, with special attention to disaster risk reduction and the "Geohazards in European Geoparks" (Pellicer et al. 2024) highlights the importance of considering the hazards in geoparks, which may attract large number of tourists.

Taking into account geoheritage and risk management plans, a new integrated proposal is presented for geosites in active volcanic zones and taking into account the volcanic hazard for visitors. For this I took as inspiration management plans in Costa Rica, Tenerife's "PEVOLCA" in Spain, Portugal, Mexico, Peru, Chile, Hawaii (USA), Indonesia, and from my firsthand experiences gained through visits to geoparks and other geosites in Europe, such as Portugal, Spain, France, Belgium, Greece, and Italy (Burek and Potter 2002; UNESCO et al. 2012; Salazar et al. 2012; Macedo 2012; Newhall 2014; Erfurt-Cooper 2014; National Park Service et al. 2016; Gobierno de Canarias et al. 2017; SRPCBA 2018; SERNAGEOMIN 2019; Secretaría de la Defensa Nacional 2019; Geoparque Granada 2019; SINAC 2020; CENEPRED and INDECI 2021; Geoparkea 2021, 2022; Griffiths and Law 2023; Alvarado et al. 2023; Pellicer et al. 2024; Agastya et al. 2024; Marotta et al. 2024; Stewart 2024).

4.1. General management structure

4.1.1. Human resources - Staff

The efficient organization of the project team is vital for its successful management, since everything depends on teamwork. Like any organization, it should have a general coordinator, preferably someone familiar with the area and who has been involved in geoheritage assessment from the early stages. If the study area encompasses multiple municipalities, it is essential to have representation from each one to facilitate coordination and organization among them.

For the setup of an interpretation strategy of geosites, it is important to have a specialized geoscientific team capable of developing interpretive material on the geological significance of the location. This team would also support proposals for geo-education, with a primary focus on topics such as volcanology and volcanic hazards. The technical information collected must be organized and reinterpreted in a didactic and understandable way for incorporation into brochures, panels, interpretation centers, and other educational materials.

Therefore, having a scientific communication team comprised of specialists in social sciences is essential to effectively transmit this information to tourists and local communities, serving as a direct link between them. In addition to technical aspects, logistic and legal matters should be addressed by an administrative team responsible for monitoring economic progress, fundraising, project applications, and other activities included in the management planning.

In general terms, this is the basic staff required to manage, generate, and transmit the information. However, depending on each site's specific requirements, this team may need to be more specialized and better structured.

4.1.2. Guides, park rangers and volunteers

Effective collaboration with guides is essential, requiring comprehensive training to ensure accurate information is conveyed to tourists. Guides and park rangers may be affiliated with private associations or companies, as they often have more extensive knowledge of local conditions than scientists. Among the diverse functions of guides is their role as disseminators of information and interpreters of geological features, aiding visitors in better understanding the value of geosites for geoeducation. Their involvement not only enhances the visitor experience but also contributes to the economic development of communities and promote responsible geotourism to minimize the impact on vulnerable sites. Implementing volunteer programs for students interested in internships or research on geological features could also be beneficial.

They can also serve as first responders in case of an event, and can manage crises, and observe activity. Ensuring tourist safety by guiding them along designated paths, highlighting potential hazards, and providing assistance during emergencies or natural disasters is essential. Moreover, guides and volunteers can further engage with local communities, supporting local businesses and safeguarding cultural heritage.

4.1.3. Support institutions, partners and sponsors

Staff may get the support from partners, national and international institutions, and sponsors. Partners may include technical-scientific institutions that can provide information on the geology of the volcano, hazard maps, and current volcanic activity status. Additionally, it is relevant to collaborate with institutions capable of enhancing the visibility of geosites by disseminating relevant information through local businesses, accommodations, and restaurants.

In summary, support institutions, partners, and sponsors are integral to the sustainability and success of geoheritage areas. Their contributions in terms of financial resources, technical expertise, operational support and engagement are vital for the protection, promotion, and sustainable use of these valuable natural resources.

4.2. Overview of the study area

4.2.1. Description of the territory, resources, and volcanic activity

In the management plan reports, it is essential to present an engaging, informative, and accessible overview of the geoheritage of the territory. This starts with a general description of the geography, its geodiversity, and its influence with the biodiversity of volcanic areas. Additionally, for all climates, and especially for tropical zones, it is important to provide a description of the climate and the best times of the year to visit. Regarding volcanic activity, it is fundamental to provide adequate information about the types of volcanoes present, the volcanic activity in the area, its eruptive history, and impacts, highlighting key sites with volcanic features of scientific, educational, and touristic interest, inventoried as geosites.

4.2.2. Description of the geosites

In a management plan, it is essential to provide a concise description of geosites, detailing their precise location, boundaries, notable geological features, formation, and origin. Additionally, it is important to highlight their scientific, educational, and touristic significance. Using clear and accessible language ensures that both specialists and the general public can understand the information, emphasizing the relevance of the geosite within the managed area and its contribution to the natural and cultural value of the territory.

4.3. Geosite management planning

4.3.1. Accessibility, signalling, and interpretive panels

The logistics are crucial for promoting geosites. Improving access roads and signage to geosites, georoutes, or viewpoints is essential for attracting the attention of tourists or visitors. Road signs near geosites increases their visibility, preventing from being overlooked. Conducting a main evaluation helps determine which geosites require appropriate signage or need the installation of paths and handrails for safety. Moreover, interpretive panels play a vital role and should be meticulously prepared by the technical team (as the dissemination material). This involves evaluating the information to be included, determining the language and terminology, selecting appropriate visuals such as photographs, cartoons, or diagrams, deciding on the placement, providing suggestions for other geosites, incorporating inclusive language, and including QR codes that direct visitors to the website for more information.

To facilitate the advancement of geotourism, it is important to incorporate geosites into different thematic georoutes, including the diverse interests of tourists. These routes should encompass a range of cultural or educational activities, providing visitors with a good experience. By offering a variety of georoutes with differing durations, content, and difficulty levels, destinations can appeal to a broader audience. Regular maintenance checks on access routes, particularly dirt roads, should be conducted to ensure they are in optimal condition for evacuating visitors from high-risk geosites in the event of an unexpected eruption. Furthermore, it is fundamental to have clear signage indicating restricted and/or dangerous areas in these sites, if necessary. Likewise, it is important to encourage tourists to respect these signs and follow the recommendations to ensure their safety during their visit.

4.3.2. Geosite protection actions

Geosites in active volcanic zones, with recent pyroclastic deposits dating back to the Holocene, are relatively fragile and vulnerable to erosion. Similarly, geosites in geothermal areas also exhibit fragile deposits (Migoń and Pijet- Migoń 2016). Therefore, it is necessary to identify the most vulnerable sites and propose safety measures to prevent the deterioration of these areas of interest.

To mitigate degradation caused by human activities, it is essential to provide proper infrastructure to prevent contact with certain deposits, implement signage to restrict access to sensitive areas, and create designated trails and rest areas to minimize the impact of tourism on volcanic terrain. Additionally, access to some areas should be limited, and if necessary, restrictions on sample collection should be enforced, with alternative methods offered for educational and scientific purposes. For natural causes like erosion, measures such as reforestation, the use of vegetative barriers, and physical protective structures can help reduce soil erosion. These efforts will ensure that volcanic deposits are preserved for future generations, maintaining their scientific, ecological, and aesthetic value.

In other recent alternative techniques for volcanic deposits with stratigraphic relevance, new methods have emerged for extracting samples and ensuring their preservation so that they can be taken to museums or interpretation centers. One such technique involves using epoxy resin on pyroclastic fall deposits, which, due to their porosity, can be impregnated into the resin and extracted in blocks (Douillet et al. 2018; Morin et al. 2024).

4.3.3. Geosite zoning according to "visitor risk assessment"

Zoning geosites based on visitor risk assessments can ensure their safety while also allowing visitors to responsibly experience and appreciate the geological wonders of volcanic areas. It is essential to remember that interpretation is done according to the alert level system (Figure 12, Table 10). In a state of normal activity, geosites are generally safe, and all tourist, educational, and scientific activities can proceed without disruption. However, if volcanic activity escalates from green to orange to red, geosites identified as being on alert can still be visited, but visitors should remain aware of current restrictions. Finally, access to geosites marked as restricted must be strictly limited or prohibited during volcanic alerts or eruption events.

4.4. Geoeducation and geotourism management

4.4.1. Geoeducation

The interpretation and promotion of geosites involves the production of dissemination materials, such as brochures, flyers, postcards, books, comics, and videos, providing visitors with tangible and memorable souvenirs. Collaboration with a graphic designer is decisive to achieve aesthetically pleasing and visually organized materials, enhancing their effectiveness in engaging audiences and conveying the intended message. In fact, it is essential to consult and involve the public from an early stage in the production of dissemination materials and to consider the perceptions of tourists and local residents regarding geosites. This can be achieved through the use of sketches, diagrams, and by actively listening to their suggestions.

An interpretation center is a valuable asset, offering a general introduction to the geosites and their geological and cultural significance in a didactic and educational way. This center should utilize models, diagrams, and experiments to captivate visitors of all ages, including children. Moreover, incorporating multimedia materials such as educational videos and virtual reality experiences enhances the understanding of volcanic hazards and benefits. Additionally, exhibiting different volcanic products, geological maps, hazard maps of the volcanoes, and real-time monitoring data provides visitors with a complete and immersive experience. This approach ensures that visitors gain a thorough understanding of the geological features and associated risks and benefits, making their visit both informative and memorable.

4.4.2. Geotourism and cultural programs

Both the local population living near volcanoes and the tourists visiting these areas should be well-informed about volcanic hazards. This can be achieved using geosites in an engaging and educational manner. Promoting the natural beauty of these landscapes through geotourism with georoutes connecting these sites to other cultural activities helps to establish a bond with the communities. Geotourism also involves encouraging young people and children to incorporate these topics into their educational interests, thus promoting research or encouraging university students to carry out specialized studies in geosites of scientific importance. This contributes to a deeper understanding of volcanic activity and its implications.

Lastly, since this type of geotourism has a potential risk, it is essential to continuously inform and raise awareness among visitors to stay informed about technical reports on the volcano's status before their visit. There should be coordination with guides to inquire and gather information to ensure all geosites are safe to visit. Disseminating information about volcanic hazards in this way helps visitors feel secure and reassured that they are in a prepared place in case of an emergency.

4.5. Volcanic risk mitigation measures

The management of volcanic risks in geotourism areas should be addressed comprehensively and proactively. This involves implementing prevention and response measures to mitigate the risk of potential volcanic events such as eruptions or lahars. It is essential to follow a structured approach, considering the volcanic risk management cycle (Figure 15), that describes the actions to take before, during, and after the event to effectively manage potential hazards for visitors. These measures are detailed in this subsection on mitigation measures and in the contingency plan.

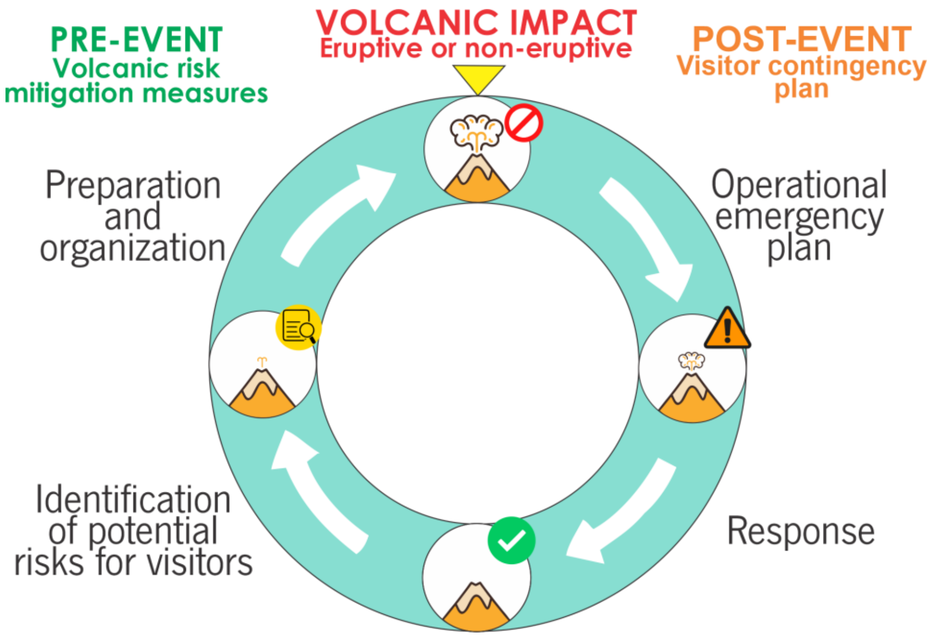


Figure 15. Volcanic risk management cycle using geomojis integrating mitigation measures and the contingency plan for visitors. (Modified from Schneiderbauer and Ehrlich 2004; Shires and Van Wyk de Vries 2024).

4.5.1. Identification of potential risks for visitors

There are geosites with potential hazards to tourists, ranging from volcanic eruptions, fumarolic activity, rock fall due to earthquakes, and weather events that can produce floods, and lahars during rainy periods, or unstable areas prone to sliding or collapse. In addition, tourists can have accidents on steep slopes, cliffs and deep quebradas, get lost in thick jungle, etc. This mean that visitors themselves can be an agent in the hazard, causing their own problem, rather than being impacted by an imposed event. Many of these issues are often not adequately addressed in management plans. Therefore, identifying these potential risks is essential. Attracting tourists brings the responsibility to monitor volcanic activity and have contingency and emergency response plans as an essential part of management (Casadevall et al. 2019; Tormey and Casadevall 2022).

The identification of volcano activity commonly employs alert level systems (Table 10), depicted through volcano alert light systems, for easy and quick understanding to facilitate decision-making. Typically, these systems are developed and shared by technical-scientific entities specialized in volcano geology and real-time monitoring. In the event of any changes or anomalies, these entities update the volcano alert level and communicate it to civil defence or risk management agencies, who then relay the information to relevant authorities and the public.

An illustrative example of unified volcanic alert levels (Table 10) comes from institutions such as Peru's Instituto Geológico Minero y Metalúrgico (INGEMMET), Mexico's Centro Nacional de Prevención de Desastres (CENAPRED), and the Special Civil Protection and Emergency Response Plan for Volcanic Risk in the Canary Islands, Spain. (Mariño et al. 2007; Gobierno de Canarias et al. 2017; CENAPRED et al. 2023). These clear examples show how volcano activity evolves, triggering changes in the color-coded alert level system.

Table 10. Description of volcanic scenarios according to the volcanic alert light system.

VOLCANIC ALERT LIGHT	**PHASE**	**VOLCANO SITUATION**
Green (Normal)	Phase 1 - Volcano at rest	• The volcano is in a state of rest • Stable conditions
	Phase 2 - Minimal signs of activity	• Emission of gases, mostly water vapor • Occasional low-intensity seismic activity • Fumaroles up to 500 meters in height
Orange (Alert)	Phase 1 - Signs of activity	• Increase in local seismic activity • Sporadic and light ash emissions
	Phase 2 - Increased activity	• Increase in fumarole emissions over 500 meters, accompanied by noise • Light ash falls in nearby areas • Light explosions that may launch ballistic materials around the crater
	Phase 3 - Intermediate to High Activity	• Light to moderate surface deformation of the volcano • Persistent fumaroles, gases, and moderate ash falls in nearby areas • Increasingly intense explosions with the ejection of incandescent ballistic materials • Possible medium-range pyroclastic flows • Acid rain and water contamination • Occurrence of lahars (mudflows)
Red (Alarm)	Phase 1 - Explosive Activity of Intermediate to High Hazard	• Critical volcanic activity with intense and prolonged earthquakes • Eruptive column several kilometers high with incandescent ballistic materials on the volcano's slopes • Collapse of the eruptive column or dome destruction that may produce pyroclastic flows reaching up to 10 kilometers • Heavy ash emissions with regional impacts and widespread acid rain

	• Formation of extensive lahars • Emission of lava flows
Phase 2 - Explosive Activity of High to Extreme Hazard	• High-reaching eruptive columns • Intense ash and lapilli emissions over large distances • Collapse of the eruptive column or dome destruction that may produce pyroclastic flows reaching up to 15 kilometers • Imminent hazard of partial collapse of the volcanic structure due to explosions • Formation of large lahars with potentially devastating effects • Emission of large lava flows

4.5.2. Organization and preparation

4.5.2.1. Cooperation with support organizations

The team responsible for managing geosites requires support of both national and international technical and scientific entities. This includes institutions dedicated to geological and volcanological studies, as well as those specialized in real-time monitoring of volcanic activity. Additionally, collaboration with civil defence institutions, municipalities, risk management organizations, national police, health centers, organizations like the Red Cross, non-governmental organizations (NGOs), and other stakeholders is fundamental. Their contribution of information, resources, and support is essential for effective risk management.

4.5.2.2. Team organization and staff equipment

The coordination of geoheritage sites must ensure that all personnel, including workers, guides, and park rangers, receive comprehensive training on topics such as general volcanology, volcanic hazards, monitoring techniques, interpretation, and the significance of each phase of the volcanic alert system. It is also essential to provide safety equipment such as protective eyewear, helmets, masks, gloves, etc., for both staff and visitors in case of emergencies, and possibly even for normal conditions. This also includes the addition of security cameras, communication radios, and alert networks such as megaphones for the rapid dissemination of alerts.

In geosites management, implementing visitor control measures, especially for sites situated close to volcanoes (high and moderate hazard zones), is essential. For geosites experiencing significant tourist or educational demand without established tourist control or emergency plans in the event of an eruption, urgent implementation of such measures is critical. Incorporating an administration and control office into the initial stages of the General Management Project is necessary, particularly focusing on the geosites closest to the volcano and expected to attract the highest number of visitors.

Conducting volcano eruption drills for personnel, guides, park rangers, and visitors is vital for preparedness, ensuring everyone understands evacuation procedures. Critical components of emergency preparedness include appointing a director responsible for coordinating all actions during an emergency, monitoring changes and evolution of volcanic phases, and delegating communication tasks.

4.6. Visitor contingency plan

4.6.1. Operational emergency plan

In response to a change in the status of geosites due to a volcanic eruption, an operational plan must be implemented to facilitate rapid and sequential decision-making based on priorities. This applies if the volcanic eruption was anticipated and reported through a progressive change in the alert level from green to orange, or in the event of a sudden scenario without any premonitory signs, leading to a significant and abrupt eruption that changes the alert level from green to red.

There are few volcanic geoheritage areas that have a contingency plan for visitors. A couple of good examples are in Costa Rica, with the Turrialba volcano and Poás volcano national parks (Salazar et al. 2012; SINAC 2020) or in Lanzarote Spain the PEVOLCA plan (Gobierno de Canarias et al. 2017), which served as inspiration for this proposal.

The action plan presented in Figure 16 serves as a step-by-step guide on how to act in an emergency situation. In an ideal scenario, where there is a well-established management plan, geosites have been previously located on hazard maps, and there is effective geosite administration. This action plan can be adapted for specific cases according to the area of study. Finally, it is essential to stay updated on volcano activity reports, whether there is an increase or decrease in activity, to continuously monitor and close access routes to restricted areas, maintaining control over visitors.

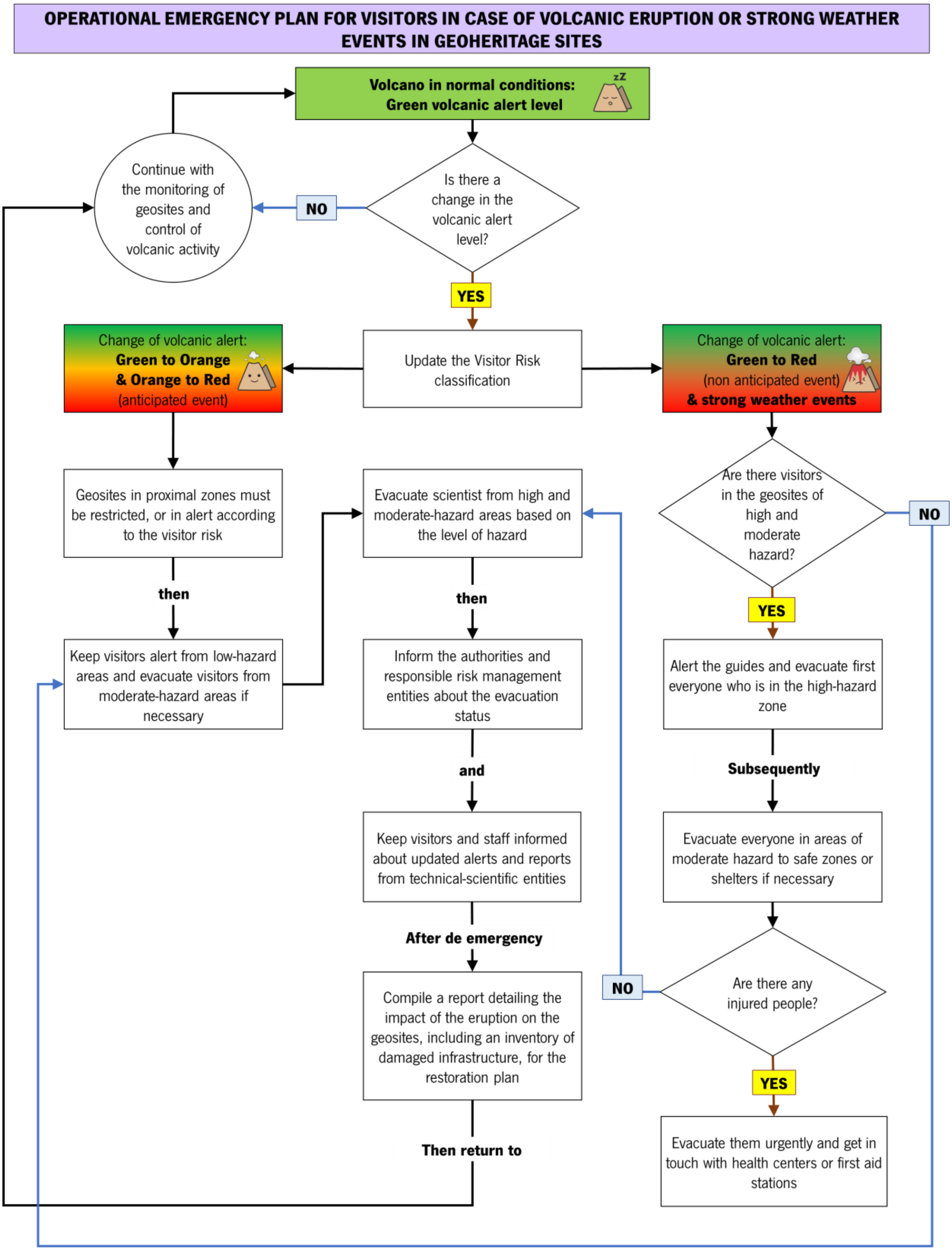


Figure 16. Operational emergency plan for visitors in case of volcanic eruption or strong weather events in geoheritage sites.

When the volcanic alert concludes and the state returns to green, it is important to verify if there are any significant physical damages to the geosites and structures through an inventory or checklist. Then the maintenance of access routes and structures should be conducted before reopening to visitors following the eruption. Additionally, considering that as a result of volcanic eruptions it also allows us to identify possible new geosites.

4.6.2. Response

The response after an eruption event includes the restoration, which is the recovery process after an eruption or event, to mitigate and mend the harmful effects, which affect the infrastructure and can cause human losses in the surrounding areas. The impact of large eruptions has happened to different populations around the world. The national organizations that manage disaster risk and their local authorities are those generally in charge of dealing with these emergencies, but all sectors can be concerned with restoration. Many recovery plans focus on economic rehabilitation due to damage to both public and private infrastructure, agricultural areas, harm to the ecosystem (including flora and fauna), and potential physical harm to individuals. These plans aim to enhance resilience in areas continually affected by volcanic activity. For instance, in Hawaii, there is the "Kilauea Recovery and Resilience Plan" (County of Hawai‘i Recovery Team 2020).

It is essential to establish internal controls to manage potential losses and assess the impact on infrastructure in the geosites in the event of an eruption. One way to implement internal control is by maintaining a prior inventory of structures and equipment installed at the geosites, such as interpretive panels, signage, and security infrastructure (e.g., security fences, stairs, viewing platforms, etc.). Additionally, it is advisable to adhere to the restoration plans outlined by local municipalities and civil defense or risk management entities for each locality. These can be co-constructed with the geoheritage management plan for each geosite.

Currently, the scientific community has made significant advancements in using tools and methods to prepare people for natural phenomena, including predictive models, monitoring instruments, and early warning systems. However, it is also crucial to consider ethical and social aspects to prepare for and recover after a disaster (Peppoloni 2023).

This ability to recover is known as resilience. While communities may initially experience detrimental effects from an external event, including human and material losses, economic problems, and traumatic events, it is essential to recognize that natural phenomena can also bring benefits. These include water, new soils, and mineral resources. For geoscientists, these events present opportunities to study new rock formations and discover amazing sites that can become geotourism attractions.

It is important to convey to tourists visiting these active volcanic sites that, while the hazard cannot be entirely avoided, vulnerability can be reduced. Visitors should be informed that, in the event of an eruption or other emergency, knowing how to act and recover is important, also generating respect for those recently vulnerable sites and their communities. These geosites can serve as educational tools, offering technical information and acting as open books on the volcanic history of the area.

A current project that aligns with this approach is UNESCO's IGCP 692: Geoheritage for geohazard resilience (geopoderes.com). Since its inception in 2019, this project aims to use geoheritage sites to communicate and raise awareness about natural hazards and associated risks. It also seeks to explore the relationship between these sites and local communities, enriching their knowledge and fostering resilience against natural events.

4.7. Monitoring and periodic review

4.7.1. Monitoring of geosites

Monitoring the current state of geosites is essential for implementing conservation measures effectively, building upon the results of previous evaluations, and ensuring their ongoing success. This monitoring process involves conducting periodic assessments of the condition of geosites, utilizing photographic records and notes tailored to the scale of each site. For larger geosites, UAV and satellite images may be employed, while smaller-scale geosites may require detailed records of the physical characteristics of each geological element. By systematically documenting the state of geosites over time, authorities can track changes, identify potential threats or degradation, and take proactive steps to preserve these valuable natural resources.

As part of the monitoring, to prevent degradation caused by overtourism, it is decisive to assess the carrying capacity of tourists at geosites periodically, particularly those susceptible to high levels of degradation. The methodology proposed by Santos and Brilha (2023) offers a valuable framework for addressing this issue and can be adapted to our study area. Priority should be given to recent volcanic deposits, as many geosites featuring volcanic deposits, especially those of relatively recent origin in geological time, remain unconsolidated. Examples include pyroclastic flows, tephra falls, and pyroclastic waves, among others. These deposits are highly susceptible to erosion and can undergo significant loss of quality over time.

By implementing measures to manage visitor numbers in alignment with the carrying capacity of these sensitive sites, we can mitigate the adverse impacts of overtourism and ensure the long-term preservation of these significant geological features. Similarly, conservation measures should be implemented to prevent the total loss of these features. Such measures may include physical stabilization techniques, vegetation management to reduce erosion, strategic placement of barriers or fences to limit access, and ongoing monitoring to track changes and intervene as necessary. By safeguarding these vulnerable geological features, we can preserve valuable scientific and educational resources for future generations.

4.7.2. Periodic review of volcanic activity to update visitor risk

Prompt action is imperative to update the status of each geosite upon receiving a report indicating a change in volcanic alert level from green to orange and to red. Following the examples provided previously (Table 8, 9), geosites designated with orange and red levels immediately change to alert status. Restrictions and carrying capacity may apply to these geosites, as advised by specialists. Should the alert level escalate to red, geosites in this category also become restricted, with tourist activities prohibited. Access is limited to experts for research purposes, equipped with the necessary safety equipment if deemed necessary. Finally, in the event of a cessation of volcanic activity and a return to normal conditions, indicated by a green status (Table 6, 7; Figure 15, 16), all geosites should be considered open to visits.

V. DISCUSSION

5.1. Threats and Challenges

There are many threats and challenges faced by the management of geoheritage in active volcanic areas and these can complicate the operation of these sites. Addressing these threats requires careful planning, adequate resources, collaboration among partner institutions, and cooperation among local authorities, scientists, and tourism administrators to ensure the safety of visitors and the sustainability of volcanic geoheritage.

Currently, many volcanic tourist sites are visited each year by large numbers of tourists attracted by their landscapes and the possibility of witnessing an eruption. However, in the event of a volcanic emergency, attracting tourists without the necessary experience, preparation, and knowledge of how to handle these situations is a real threat, especially if they are not provided with accurate information. One challenge to overcome is to tackle the idea that talking about volcanic risk could "scare off" visitors and affect economic income. It should be understand that disseminating truthful and transparent information will make visitors feel safer knowing they are in a place where people are prepared and know how to act in any emergency.

However, there is also the flip side of the coin, where even with knowledge, dissemination, and trained guides providing necessary recommendations, a residual problem lies in raising awareness among visitors about the hazards and ensuring compliance with rules and recommendations. There are many cases of visitors, seeking adrenaline and adventure, who risk their lives by approaching dangerous areas, despite the signage, guide instructions, or even venturing without them. Some even try to bribe guides to access these areas, putting not only their lives at risk but also those of the rescuers. This is a topic that still requires much work.

Another threat and challenge to improve is the lack of a good relationship with the local communities living daily alongside the volcanoes. These communities may feel pressured by tourist planning decisions or an excess of tourism that does not respect their space or feelings, especially when they have been recently affected by an eruption. It is essential that visitors are respectful and empathetic towards the local communities. Likewise, managers, geoscientists, and coordinators of these geotourism areas must maintain horizontal, participatory, and transparent communication with the local communities. In many cases, the empirical knowledge of residents can provide a perspective that enriches the scientific viewpoint. Therefore, it is important to consider their opinions, as well as those of the visitors, and recognize them as authors and disseminators of information. In this way, local communities can be encouraged to take the initiative in the development and organization of geosites, especially in private spaces, without feeling pressured or obligated, but rather motivated by their own interest and as a support in emergency management.

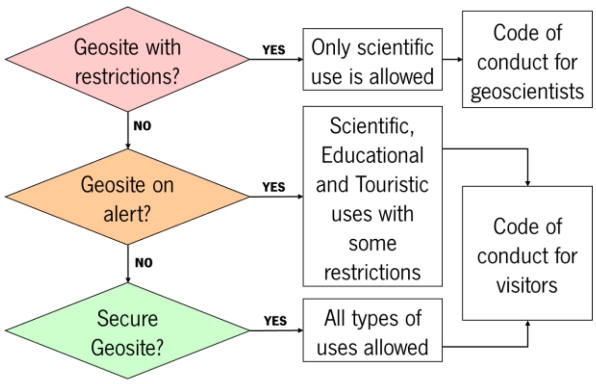
5.2. Opportunities

Geotourism in active volcanic zones is a reality that attracts many visitors, making it essential to assess the level of hazard we are exposed to and to have an appropriate management plan in place, especially for geosites used for tourism and education, while also preserving the value of these geosites. Additionally, geotourism presents an opportunity to address volcanic geoheritage and risk management issues collectively and comprehensively. It can serve as a tool for communicating topics related to hazards, risks, and resilience to these natural phenomena through geoeducation.

Integrating visitor risk assessment into geoheritage inventories and developing a management plan that includes risk mitigation and contingency plans for visitors (Table 11) is a critical initial step in addressing geological hazards holistically. This involves anticipating the identification of the most vulnerable geosites for visitors in response to any changes in volcanic activity or extreme weather conditions, which may also trigger hazards such as lahars or floods, complicating access and communications. This approach ensures a prompt response and timely decision-making for the safety of visitors, workers, guides, and others involved.

This proposal can be improved to adapt to the unique geoheritage characteristics of each territory. It is time geoconservation to integrate these criteria into geosite inventories and management plans. Just as the geological nature is beautiful, it can also be dangerous, and we must be prepared for it. Finally, a significant opportunity in active volcanic zones is the potential to identify new geosites as a result of volcanic activity; this is important from a tourism, scientific, and educational perspective.

Table 11. Summary table of the proposal for assessment and management of geoheritage in active volcanic areas.

<table>
<tr><th colspan="2">ASSESSMENT METHODOLOGY FOR GEOSITES IN ACTIVE VOLCANIC AREA</th></tr>
<tr><td colspan="2">Inventory of geological sites</td></tr>
<tr><td colspan="2">Identification of potential sites
Fieldwork and selection of geosites
Qualitative assessment and characterization</td></tr>
<tr><td colspan="2">Numerical assessment</td></tr>
<tr><td colspan="2">Scientific use
Educational use
Touristic use
Geosite risk
Visitor risk</td></tr>
<tr><td>Geosites sorted by the scientific, educational, touristic use and geosite risk</td><td>Geosites sorted by security status according to "Visitor risk"</td></tr>
<tr><td>Interpretation and classification of geosites
Level geosite risk or degradation (high, moderate and low) for geoconservation</td><td>
</td></tr>
<tr><th colspan="2">MANAGEMENT PLAN FOR GEOSITES IN ACTIVE VOLCANIC AREAS</th></tr>
<tr><td colspan="2">General management structure
Overview of the study area
Geosite management planning
Geoeducation and geotourism management
Volcanic risk mitigation measures
Visitor contingency plan
Monitoring and periodic review</td></tr>
</table>

VI. CONCLUSIONS

Geotourism in active volcanic areas presents a complex balance between the sustainable use of unique natural resources and the mitigation of geological risks for visitors. These sites, being geologically dynamic, offer high geodiversity, dramatic landscapes, mineral resources, and are habitat for many species. However, they also pose significant threats, particularly by attracting thousands of tourists each year.

While volcanic hazards are mostly unpredictable, technological advancements have allowed for the development of early warning systems that detect precursor events using geological and geophysical techniques. Together with the risk maps, these tools are valuable in minimizing impacts. Taking advantage of this background, combined with field data in "visitor risk" assessment, will enable us to identify the most vulnerable geosites and make timely decisions for both anticipated and unexpected events.

It is the responsibility of geoheritage managers and administrators to be trained and have management plans in place that guarantee the preservation of the value of these sites and ensure good experiences for visitors. These plans should include risk mitigation and contingency strategies, in harmony with territorial management plans, to enhance visitor safety in case of an emergency. Likewise, visitors should respect the signs indicating dangerous areas and follow the recommendations of guides or park rangers, in order to avoid unnecessary risks and disturbance to the habitat of local species.

Integrating these criteria into the assessment and management of geoheritage not only ensures the safety of visitors but also ensures that workers are informed about the hazards in their workplace and know how to act in response to them. In the case of guides, it is important that they do not succumb to the temptation for financial gain over safety, or to bribery from visitors who want to surpass hazard signs and access restricted areas, as this puts their own lives at risk. Therefore, it is important that geotourism as an economic activity ensures fair income for workers and decent working conditions.

This underscores the importance of geoeducation, raising awareness about natural phenomena, and risk management through geotourism. Geosites should be used as open-air laboratories and schools, where both visitors and geoscientists can learn from local people who live alongside the volcanoes, thereby increasing their resilience to geological hazards.

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