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Comparative analysis of geosites in volcanic areas: Tungurahua Volcano Aspiring Geopark (Ecuador) and Tenerife Island (Spain) as case studies

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Dissertação de Mestrado
Mestrado em Geociências
Área de Especialização em Património Geológico e Geoconservação

Trabalho efetuado sob a orientação de
Doutor José Bernardo Rodrigues Brilha
Doutor Javier Dóniz Páez

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Statement of Integrity

I hereby declare that this thesis is my original work and has not been submitted for any degree or diploma at any other institution. I have acknowledged all sources of information and assistance appropriately, and have ensured that this work is free from plagiarism. This declaration is made in accordance with the ethical guidelines of academic integrity.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

Comparative Analysis of geosites in Volcanic Areas: Tungurahua Volcano Aspiring Geopark (Ecuador) and Tenerife Island (Spain) as case studies

Abstract

Geoparks play a vital role in preserving geological heritage and promoting sustainable development through geotourism. While many regions in South America and the Caribbean are seeking UNESCO Global Geopark recognition, numerous geoparks in Spain and Europe have already achieved this status. However, regions like Tenerife, despite not being officially designated as geoparks, still possess valuable, internationally recognized geological heritage. This master disertation explores two volcanic regions: Tungurahua Volcano Aspiring Geopark (TVAG) in Ecuador, located in a subduction zone, and Tenerife Island (TI) in the Canary Archipelago, Spain, situated in an intraplate zone. The main objective was to propose guidelines for evaluating the volcano tourism potential of geosites in volcanic areas, irrespective of their geotectonic and social contexts. Twenty-one geosites were identified in TVAG and eleven in TI, classified based on their origin and processes. The assessment used a quantitative scale from 0 to 1, evaluating scientific values (integrity, representativeness, rarity, and interest) and additional values (ecological, aesthetic, cultural, and economic). Results revealed significant differences in the geotectonic contexts, thus, TI geosites presented higher values, particularly in stratovolcanoes and calderas in scientific criteria due to minimal landscape changes by its low volcanic activity. Conversely, TVAG exhibited lower values in integrity and representativeness due to frequent volcanic activity but excelled in glacial and periglacial materials with higher representativeness and rarity values. TVAG also showed higher values in pyroclastic deposits and lava flows, influenced by its recent volcanic activity. Pearson correlation indicated a moderate-high positive correlation (r=0.77) between scientific and additional values, suggesting that geosites with high scientific values often have high additional values. Geosites were classified into high, medium, and low categories for management and conservation purposes. High-value geosites, such as Tungurahua volcano in TVAG and Teide Pico-Viejo in TI, constitute 74% of the total and require priority in conservation efforts. Overall, this research provides a comprehensive framework for assessing and developing geotourism in volcanic areas, emphasizing the need for tailored conservation and promotion strategies, such as improving infrastructure in Tungurahua and enhancing scientific communication in Tenerife. These findings support sustainable management and protection of volcanic geoheritage, boosting geotourism potential in both regions and offering valuable insights for other volcanic areas worldwide.

Keywords: Geoparks, geotourism, geoheritage, geoconservation, sustainability

Análise comparativa de geossítios em áreas vulcânicas: o Geoparque Aspirante Vulcão Tungurahua (Equador) e a Ilha de Tenerife (Espanha) como estudos de caso

Resumo

Os geoparques desempenham um papel vital na preservação do património geológico e na promoção do desenvolvimento sustentável através do geoturismo. Enquanto muitas regiões da América do Sul e das Caraíbas procuram o reconhecimento como Geoparques Globais da UNESCO, numerosos geoparques em Espanha e na Europa já alcançaram este status. No entanto, regiões como Tenerife, apesar de não serem oficialmente designadas como geoparques, possuem um valioso património geológico reconhecido internacionalmente. Esta dissertação de mestrado explora duas regiões vulcânicas: o Geoparque Aspirante do Vulcão Tungurahua (TVAG) no Equador, localizado numa zona de subducção, e a Ilha de Tenerife (TI) no Arquipélago das Canárias, Espanha, situada numa zona intraplaca. O principal objetivo foi propor diretrizes para avaliar o potencial de geossítios para o geoturismo vulcânico em áreas vulcânicas, independentemente dos seus contextos geotectónicos e sociais. Foram identificados vinte e um geossítios no TVAG e onze em TI, classificados com base na sua origem e processos. A avaliação utilizou uma escala quantitativa de 0 a 1, avaliando valores científicos e valores adicionais1. Os resultados revelaram diferenças significativas nos contextos geotectónicos; assim, os geossítios de TI apresentaram valores mais altos, particularmente em estratovulcões e caldeiras em critérios científicos, devido a mínimas mudanças na paisagem pela sua baixa atividade vulcânica. Por outro lado, o TVAG exibiu valores mais baixos em integridade e representatividade devido à frequente atividade vulcânica, mas destacou-se em materiais glaciais e periglaciais com valores de representatividade e raridade mais altos. O TVAG também mostrou valores mais altos em depósitos piroclásticos e fluxos de lava, influenciados pela sua recente atividade vulcânica. A correlação de Pearson indicou uma correlação positiva moderada-alta ($r=0.77$) entre valores científicos e adicionais, sugerindo que geossítios com altos valores científicos muitas vezes têm altos valores adicionais. Os geossítios foram classificados em categorias de alta, média e baixa para fins de gestão e conservação. Geossítios de alto valor, como o vulcão Tungurahua no TVAG e o Teide Pico-Viejo em TI, constituem 74% do total e requerem prioridade nos esforços de conservação. No geral, esta pesquisa fornece uma estrutura abrangente para a avaliação e desenvolvimento do geoturismo em áreas vulcânicas, enfatizando a necessidade de estratégias de conservação e promoção adaptadas, como a melhoria da infraestrutura no Tungurahua e a ampliação da comunicação científica em Tenerife.

Palavras-chave: património geológico; geoparques; geoturismo; geossítios; sustentabilidade

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1. INTRODUCTION AND BACKGROUND

The conservation and promotion of geoheritage have garnered increasing international interest, reflecting a growing awareness of the significance of preserving this resource. In this regard, geotourism, a recent tourism modality, has increased in recent years coinciding with the creation and consolidation of the Global Geoparks Network (Carcavilla et al., 2011). Geotourism can be approached from two perspectives: geological and geographical, both approaches share a strong scientific and educational value (Dóniz-Páez & Ramírez-Becerra, 2020). Geotourism projects within a geological approach focus on ex-situ and in-situ geological resources with high scientific value, and their potential educational and touristic use associated with cultural and ecological value, which can be utilized by society, for example, to support a national geoconservation strategy (Brilha, 2016). On the other hand, the geographical approach adds environmental concepts, where abiotic, biotic, and cultural aspects interact with each other (Dowling, 2013; Chen et al., 2015, 2020; Dowling & Newsome, 2018)

One of the geotourism modalities that has recently gained popularity is geotourism in volcanic environments, also known as volcano tourism (Dóniz-Páez et al. 2020). This activity involves visiting active, dormant, or extinct volcanoes that possess natural and cultural heritage attracting visitors (Sigurdsson & Lopes, 2000; Dóniz-Páez, 2012, 2014; Dowling, 2013). Thus, volcano tourism includes a variety of resources and tourist attractions related to natural and cultural heritage (Megerssa et al., 2019), such as landscapes, eruptive manifestations, hot springs, beaches, adventure sports, cultural parks, and the connection between volcanoes and religion (Sigurdsson & Lopes, 2000; Dóniz-Páez, 2014).

According to Dóniz-Páez et al. 2020, in order to develop the volcanic touristic interest, it is important to inventory and evaluate geosites. The inventory and assessment of significant examples of geodiversity are important steps in geoconservation strategies and in setting management priorities for sites like natural parks or geoparks (Brilha, 2016).

According to Brilha (2016) geodiversity is part of natural diversity that includes features representing the geological heritage of a territory where human activities typically occur (Herrera-Franco et al., 2022). This geodiversity encompasses elements such as geomorphological, petrological, mineralogical, paleontological, stratigraphic, structural, and hydrogeological features that result in exceptional scientific values, and understanding Earth's history (Brilha, 2016). Therefore, the conservation of this heritage entails protecting geological components and their significance in the realm of Earth Sciences, which are manifested in geoheritage sites, alternatively referred to as geosites (Fuertes-Gutiérrez & Fernández-Martínez, 2012).

Geoparks are closely associated with concepts mentioned before both geodiversity, geoheritage, and geotourism; where UGGp serving as areas with significant geological heritage managed with a coherent and robust structure (Molokáč et al., 2023).Geoparks have geological heritage that requires conservation and promotion for sustainable development (Sánchez-Cortez & Simbaña-Tasiguano, 2018). Currently, geoparks are recognized by UNESCO, highlighting the potential of a region's geological characteristics to attract visitors and contribute to local and regional development initiatives (Carcavilla Urquí & Orús, 2021). Overall, UNESCO Global Geoparks (UGGp) not only represent geological heritage but also embody the true richness of natural elements in a region, combined with the ancestral and cultural knowledge of local communities (Sánchez-Cortez, 2023).Therefore, geological conservation becomes a crucial mechanism for fostering connection and sustainable use of the territory.

Currently, there are 218 UGGp worldwide, including Transnational UNESCO Global Geoparks (UNESCO, 2024). The Regional Geopark Network shows that European (EGN) held 52% of these, with Spain contributing 8% (17 geoparks). The Asia-Pacific Geoparks Network (APGN) represented 39%, with China having 47 geoparks (22% of APGN). Latin America and the Caribbean accounted for 6%, with Brazil leading with 6 geoparks (3%), and Ecuador < 1%. The African region contributed 1% of the global total (Figure 1).

In Ecuador, nearly 90% of protected areas have geological interest, exhibiting structural, geomorphological, lithological, paleontological, or mining features (Sánchez-Cortez, 2023). Despite Ecuador's rich geodiversity and notable landmarks like the Chimborazo Fauna Production Reserve, Galapagos, Llanganates, and Sangay National Park (SNP) (Palacio et al., 2016), there remains a gap between the potential and the current efforts in conserving and promoting the country's geological heritage. Even with initiatives like the strengthening of the Ecuadorian Society for the Defence of Geological and Mining Heritage in 2007 (SEDPGYM-Ecuador) or the early significant research initiatives directed at paleontological heritage, such as the Puyango Petrified Forest in 1988 (Sánchez-Cortez, 2023), there is room for further development and improvement in strategies to leverage and protect Ecuador's geological heritage. It is important to highlight Ecuador's efforts in the field of geoheritage, such as the establishment of Equatorian Geoparks, supported by the Ecuadorian Geoparks Committee (CEG), which was established in 2019, the second one in all of Latin America (Sánchez-Cortez, 2023).

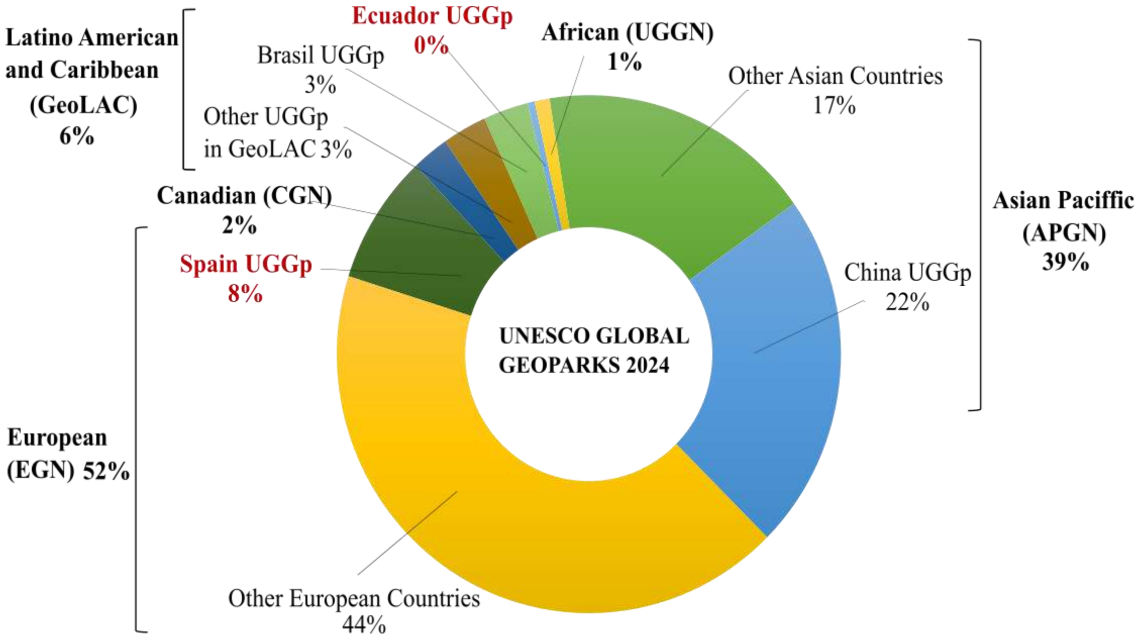


Figure 1. Distribution of UNESCO Global Geoparks (UGGp) in 2024, grouped by region (Regional Geopark Networks). The percentages are related with the total number of UGGp.

The Imbabura Geopark is the first and unique UGGp in Ecuador. However, currently, one of the significant initiatives within Ecuador's recent experience in geoheritage is the Tungurahua Volcano Aspiring Geopark (TVAG) (Sánchez-Cortez, 2023). This complex area is characterized by its active volcanism, with the Tungurahua volcano being one of the most representative eruptive centres of the geopark, and the tectonism which shaped the Cordillera Real and the Sub-Andean Zone structural model (GVT, 2023) Within this volcanic framework, the volcanic geoheritage encompasses intriguing volcanic processes that have simultaneously instilled fear, caused destruction, and offered diverse materials, prompting human societies to adapt to the new geoenvironment (Erfurt-Cooper, 2011). Consequently, geoparks featuring both active and inactive volcanism are gaining popularity (Németh et al., 2017) for example Colca and Volcanes de Andagua (Perú) and Kutraltura (Chile).

As previously mentioned, Spain has extensive experience with geoheritage and geoparks, making it the second country with more UGGp worldwide, following China (UNESCO, 2024). Some of the geoparks in Spain are located in the Canary Islands, such as El Hierro and Lanzarote-Archipiélago de Chinijo (UNESCO, 2024). It is important to note that these geoparks do not represent all of the geoheritage in the Canary Islands, for example, Tenerife Island (TI) is home to a variety of volcanic geoheritage, including the Teide National Park (TNP). As the largest island in the archipelago, Tenerife is also an important volcanic site of (Dóniz-Páez et al., 2020).

The Teide-Pico Viejo stratovolcano dominates a significant portion of Tenerife's territory, influencing its topographical, geological, geomorphological, and volcanic landscape. Due to the unique features bestowed upon it by the Teide volcano, the island has become a pivotal destination for the study of volcanology, as well as geological heritage and geoconservation. Its natural and protected areas are striving to integrate the conservation of geological heritage with sustainable development and tourism, including the volcano tourism (Dóniz-Páez et al., 2020).

Although Tenerife is achieving a high level of development in volcano tourism, the TVAG also showcases exceptional geological and geomorphological characteristics. With the increasing interest in this type of tourism, these unique features could position the TVAG as a promising and sustainable option for the development of volcano tourism. This could be a viable alternative, especially for scientific tourism, developing countries in volcanic areas, in contrast to Tenerife, which currently faces significant challenges due to the huge influx of tourists annually. The uncontrolled growth of tourism in Tenerife has raised serious concerns in recent years, despite the diverse interests of different segments of tourists (Dallavalle et al., 2021).

1.1 Objectives

The main objective of this dissertation was to propose guidelines for assessing the geotourism potential of geosites in volcanic areas, regardless of their geotectonic and social contexts. Hence, two comparative case studies were selected: Tungurahua Volcano Aspiring Geopark (TAVG) in Ecuador and Tenerife Island (TI) in the Canary Archipelago, Spain.

As secondary aims we can refer:

- To compare the geotectonic context and the volcanism that is affecting both Tungurahua Volcano Aspiring Geopark and Tenerife Island.
- To identify, select, assess, and compare volcanic geosites in continental and insular areas.
- To characterize volcanic geosites.
- To evaluate the scientific and added values in order to provide guidelines to TVAG regarding their use and conservation.
- To determine the potential for touristic development based on the evaluation of the geosites.
- To contribute to the protection and conservation of this volcanic geoheritage.
- To diversify the traditional tourist, offer within TVAG and TI by promoting volcanic tourism.

1.2 Materials and Methods

This research highlights the interaction between general tasks and their implications (Figure 2).

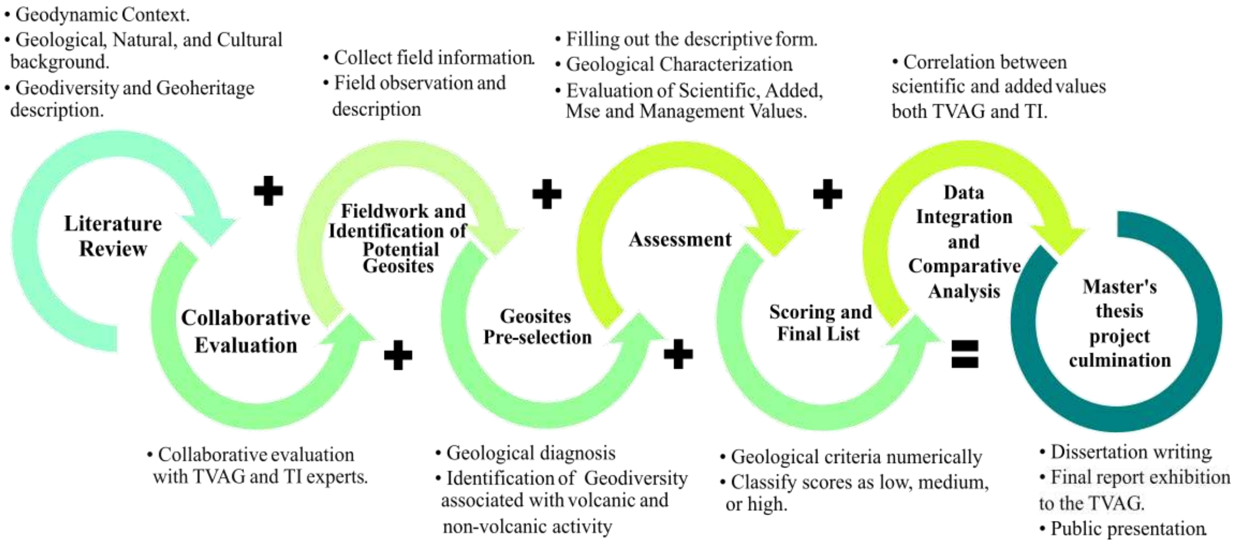


Figure 2. Workflow depicted the successive stages of the research process.

To achieve the main objective, we utilized the following resources:

- Literature Review: A comprehensive review of existing research and publications on comparative analysis (Pérez-Umaña et al., 2019), geoconservation strategies and methodologies (Brilha, 2016; Reynard et al., 2016, IGME, 2018, Dóniz-Páez et al., 2020)
- Geological Overview: A summary of general tectonic features and notable volcanic and non-volcanic geodiversity (Romero, 1991; Bustillos, 2014; Rodriguez-Gonzalez & Fernandez-Turiel, 2015; Németh et al., 2017; Bablon et al., 2019)
- Geodiversity and Geoconservation Overview: An overview of geodiversity, geoconservation, and geoheritage in Ecuadorian geoparks (Sánchez-Cortez & Simbaña-Tasiguano, 2018; Sánchez-Cortez, 2023) and Spain, specifically focusing on the Canary Islands-Tenerife (Dóniz-Páez et al., 2021; Roig Izquierdo et al., 2020).
- The identification and inventory of geosites was carried out using topographic and geological maps, along with digital terrain models and previous field studies in TVAG (Bablon et al., 2019; Bustillos, 2014; GVT, 2023; Pratt et al., 2005; Samaniego et al., 2011) and TI (Dóniz-Páez et al., 2021; Dóniz-Páez & Ramírez-Becerra, 2020; Romero, 1991).

Use of resources provided both by the Consortium's TVAG, including the geodatabase generated in its last year of management (2023-2024), and the GEOTURVOL research group, including unpublished articles and access to its geodatabase.

This study involves assessing the values of geosites, a methodology that has been successfully used in other mountainous and volcanic regions (Bouzekraoui et al., 2018; Reynard et al., 2007, 2016; Moufti et al., 2013; Pérez-Umaña et al., 2019, 2020; Tefogoum et al., 2020; Dóniz-Páez y Becerra-Ramírez, 2020; Quesada-Román y Pérez-Umaña, 2020). Key sources included Reynard et al. (2007, 2016) methodology.

This dissertation was developed in four phases: 1. Identification, inventory, and selection of geosites; 2. Geosites characterization; 3. Evaluation of the geosites considering their intrinsic values (scientific and additional); and 4. Proposed classification for the management and conservation of geosites.

1.2.1 Identification, inventory and selection of geosites

Twenty-one geosites have been identified in TVAG and eleven in TI. They have been selected, and classified based on their origin and processes, with a focus on those that share similar characteristics, such as stratovolcanoes (e.g., Tungurahua vs Teide-Pico Viejo). This classification includes specific categories for the diversity associated with volcanic activity, encompassing direct volcanic features and processes such as volcanic edifices, eruptive processes and products, and hydrothermal phenomena. Additionally, non-volcanic features resulting from erosion and sedimentary processes are also included (Carracedo Sánchez et al., 2012; Dóniz Páez et al., 2020; Erfurt-Cupper, 2021; Rodríguez-González et al., 2013; Rodríguez-González & Fernández-Turiel, 2015) (Figure 3 and Table 1).

We also followed the geoheritage subdivision mentioned by Zorina & Silantiev (2014). They suggest that it is possible to subdivide geoheritage into dozens of main interests. Thus, we distinguished morphological, stratigraphic, petrological, and geothermal types recognized in these two areas (Table 1).

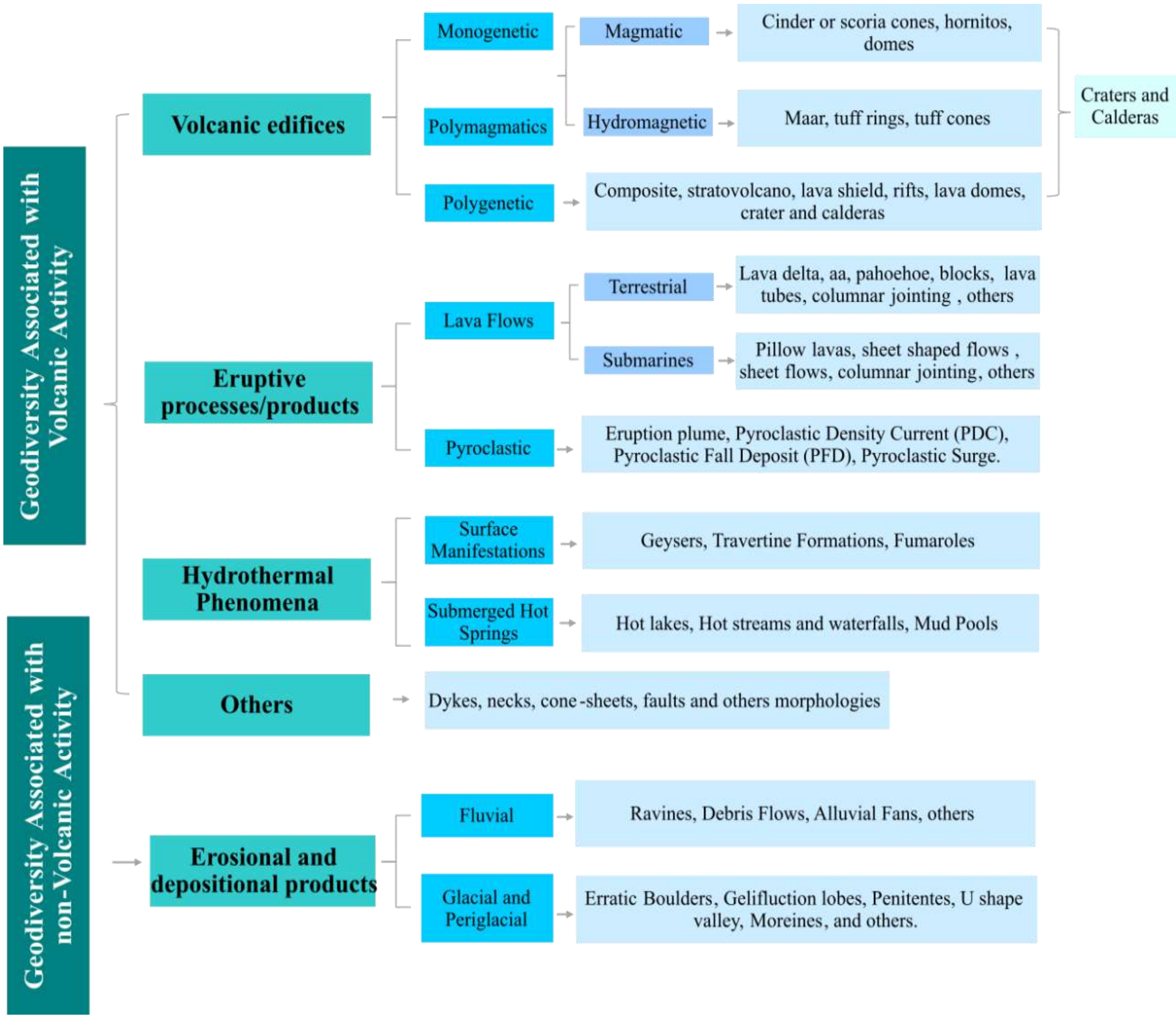


Figure 3. Scheme of volcanic diversity and geodiversity not associated with volcanic activity and geoheritage. Modified from Dóniz-Páez et al. (2020).

Table 1. Volcanic and non-volcanic diversity vs geoheritage types.

Main interest / Volcanic diversity (TVAG / TI)					Georphological	Stratigraphic	Petrological	Geothermal
Geodiversity associated with volcanic activity	Volcanic edifices	Stratovolcanoes	-Tungurahua -Chimborazo -Huisla-Mulmul -Igualata	Teide-Pico viejo	TVAG / TI		TVAG / TI	
		Calderas	El Altar	-Caldera de las Cañadas	TVAG / TI			

	Eruptive products	Lava flows		-Flujo de lava Baños -Auto-brecha de Bilbao -Deformación lávica del Huilsa-Mulmul	-Margarita de Piedra -Malpais de Guilmar -Barranco del Infierno	TVAG / TI		TVAG / TI	
		Pyroclastic Deposits	PDC	-Ignimbrita los pájaros	Tajao Ignimbrite		TVAG / TI	TVAG / TI	
			PFC	Cascada Mayorasgo	Tarta del Teide		TVAG / TI		
		Debrish Avalanche		-Hummockys de -Guanandó (30ka) -Hummockys de Cotaló (3ka) -El templete	Playa de Abadaes	TVAG / TI		TVAG / TI	
	Hydrothermal phenomena	Surface Manifestation		-Depósito de Travertino Las Caras -Aguas termales de Puela	Azulejos de Ucanca				TVAG / TI
Geodiversity not associated with volcanic activity	Erosional and depositional products	Lahars, and Aluvial Deposits		-Lahar San Pedro -Deposito Aluvial San Miguel	Rambla de los caballos	TVAG / TI	TVAG / TI		
		Glacial and Periglacial Materials		-Valle Glacial Abraspungo -Erráticos Glaciales del Chimborazo -Minas de Hielo del Chimborazo	La forteza	TVAG / TI			

1.2.2 Assessment

The assessment of geosites takes into account intrinsic values, which are further categorized into scientific (Table 2) and additional values (Table 3), as well as use and management values (Serrano & González, 2005; Reynard et al., 2007). Intrinsic values refer to those characteristics that are inherent and specific to each geosite (Reynard et al., 2016). According to Reynard et al. (2016), the intrinsic value of a geosite excludes use and management values, which can be stored in a separate database for future classification and management. Therefore, factors such as educational or geotouristic activities and protection needs are not considered in the assessment of the geosite's 'quality.' However, it is feasible use other assessments which employ quantitative methods to evaluate use and management values (Serrano & González, 2005; González et al., 2014; Kubalíková, 2019).

Table 2. Criteria used for the assessment of the scientific value. Source: Reynard et al. (2006, 2016).

SCIENTIFIC VALUE (SCI)		
Criteria	**Value**	
Integrity (I) State of conservation of the site. Bad conservation may be due to natural (e.g. erosion) or human factors	Destroyed Practically fully destroyed Partially destroyed Lightly damaged Intact	0 0.25 0.5 0.75 1
Representativeness (R) Concerns the site's exemplarity. Used with respect to a reference space (e.g. region, commune, country). All selected sites should cover the main processes, active or relict, in the study area.	Null Weak Moderate High Very high	0 0.25 0.5 0.75 1
Rareness (Rz) Concerns the rarity of the site with respect to a reference space (e.g. region, commune, country). The criterion serves to identify exceptional landforms in an area.	More than 7 Between 5 and 7 Between 3 and 4 Between 1 and 2 Unique	0 0.25 0.5 0.75 1
Paleogeographical interest (PI) Importance of the site for Earth or climate history (e.g. evolution of volcanic landscape)	Null Weak Moderate High Very high	0 0.25 0.5 0.75 1
Average	**(I+R+Rz+PI)/4**	

Table 3. Criteria used for the assessment of the Additional Values. Source: Reynard et al. (2006, 2016).

ADITIONAL VALUES			
Ecological Value (ECO)			
Criteria	**Qualitative Assessment**	**Value**	
Ecological influence	Importance of the site for the development of a particular ecosystem or the presence of a particular fauna and vegetation	- Not related to biological features. - Presence of interesting flora and fauna. - One of the best places to observe interesting flora and/or fauna. - Geomorphological features are important for ecosystems. - Geomorphological features are crucial for ecosystems.	0 0.25 0.5 0.75 1
Site protection	Consideration is taken of sites that are already protected in a national inventory, or at regional or local level for ecological reasons.	-Unprotected -Locally protected -Regionally protected -Nationally protected -Internationally protected	0 0.25 0.5 0.75 1
Aesthetic value (AEST)			
Viewpoints	Possibilities of the site to be observed. A site covered by a forest or very difficult to access would, in this case, have a lower score than a site visible from several viewpoints	-Only visible in situ or not easily accessible. -Not easily accessible, but offers 1 or 2 viewpoints. -It offers some viewpoints (3-5) due. to the presence of visual obstacles -It has many viewpoints (> 5). -It has many viewpoints and is visible from great distances	0 0.25 0.5 0.75 1

Vertical contrasts, development, and spatial structuring	Contrasting landscapes (distinction of colours); landscapes with a vertical development (mountain) or landscapes with individual elements (isolated hill) that give that space structure arc generally considered the nicest. On the contrary less contrasting landscapes, flat and monotone reliefs (e.g. alluvial plain, large plateau) are considered as not nice	-Monotonous: flat topography and monochrome. -It displays some vertical development and up to three colours are recognized. -Rugged and up to 5 colours are recognized. -It displays contrasting topography and up to 7 colours are recognized. -It displays contrasting and rugged topography, and up to 7 colours are recognized.	0 0.25 0.5 0.75 1
Cultural value (CULT)			
Religious and symbolic importance (IR)	Role of the site in the past (Presence of vestiges).	-No religious significance. -Local religious significance. -Provincial or regional religious significance. -National religious significance. -International religious significance.	0 0.25 0.5 0.75 1
Historical significance (IS)	Presence of the site in artistic realizations (e.g. paintings, sculptures) and in books or poems.	-No historical significance. -Local historical significance. -Provincial or regional historical significance. -National historical significance. -International historical significance.	0 0.25 0.5 0.75 1
Artistic and literary importance (IA)	Role of the site in the development of geosciences	-No artistic importance. -Local artistic importance. -Regional artistic importance. -National artistic importance. -International artistic importance.	0 0.25 0.5 0.75 1
Geohistorical significance (IGEO)	Role of the site in the development of geosciences	-The site is not the origin of any discovery throughout the history of Earth Sciences. -The site, due to scientific development or demonstration of a process, is locally known. -The site, due to scientific development or demonstration of a process, is known regionally and/or provincially. -The site, due to scientific development or demonstration of a process, is known nationally. -The site, due to scientific development or demonstration of a process, is known internationally.	0 0.25 0.5 0.75 1
Economic Value (E)			
Economic products	Well-known resource that generates income and benefits	-It generates no income. -It is known but causes indirect benefits (tourism). -It is a source of income but is threatened by human activity that may deplete it. -It is managed by a company, causing no impact. -It allows for direct management by an autonomous company with no negative impact	0 0.25 0.5 0.75 1
Total Average	**V.AD = (V.ECO + V. AEST + V.CULT + V.E) / 4**		

In assessing intrinsic values, authors typically employ a quantitative scale (Kubalíková, 2013; Reynard et al., 2016; Bouzekraoui et al., 2017; Pérez-Umaña et al., 2020; Tefogoum et al., 2020; Dóniz-Páez & Ramírez-Becerra., 2020). All authors agree on using a scale from 0 to 1 with intervals of 0.25. The classification is as follows: scores < 0.4 are considered low, scores from ≥ 0.4 to < 0.6 are considered medium, and scores from ≥ 0.6 to 1 are considered high (Bouzekraoui et al., 2018)

The assessment was carried out collectively, involving field experts from the TVAG and the Geoturvol Research Group. In general, results are presented as average values for comparative analysis. Scientific values are categorized based on integrity, representativeness, rarity, and interest (Table 2), while additional values are classified into ecological, aesthetic, cultural, and economic categories (Reynard et al., 2016) (Table 3).

To visualize the quantitively assessment in both areas, heatmaps, Scatter Plots, and Bar Charts were generated using Python libraries pandas, seaborn, and matplotlib (See Appendix 2). The data was organized into a pandas DataFrame, where the codes and names of the geosites were combined to form the index of the DataFrame. Subsequently, graphs were created with seaborn, and annotations were adjusted to display the corresponding values both scientific and additional values. To distinguish values, a colour scale was used to visually represent the magnitude of these values. Overall, this process ensures that the graphical representation is clear and precise, facilitating visual comparison of values across different geosites and areas.

Pearson Correlation between Scientific and Additional Values

The averages of the scientific and additional values (from TVAG and TI) were calculated for each selected geosite. When comparing these averages, Pearson's correlation was applied to determine the relationship between Scientific and Additional values. The correlation was considered low if the coefficient was close to 0, null if r was exactly 0, and high if r was close to 1 or -1, indicating a strong linear positive or negative relationship, respectively. Once the correlation graph was generated, the plot allowed us to identify groups of geosites with similar values. This grouping provided a clear understanding and a basis for decision-making in terms of the management and development of the studied geosites(Bouzekraoui et al., 2018; Marrero-Rodríguez & Dóniz-Páez, 2022). Overall, this methodology aims to conduct a thorough assessment of geosites that have the potential for geotourism in volcanic areas, as well as to make a significant contribution to the use and conservation in TVAG.

2. STUDY AREA

This chapter examines the geotectonic settings of the Tungurahua Volcano Aspiring Geopark (TVAG) in Ecuador and Tenerife Island (TI) in the Canary Islands, Spain. In terms of their geotectonic context, TVAG is situated in a subduction zone, while TI is located in an intraplate zone. Additionally, this chapter provides an overview of their environmental and cultural significance.

2.1 Geodynamic contexts

According to Schellart (2023), subduction zones are among the most complex and dramatic tectonic features on Earth and have been intensely studied, even before the advent of plate tectonics theory. They often sharing characteristics such as a deep-sea trench, magmatic arc, and Wadati-Benioff zone. Thus, there are two types of subduction zones: ocean-ocean, such as the Melanesia subduction zone, and ocean-continent subduction zones, like the South American subduction zone (Andes Mountain chain). To provide an idea of how long a subduction zone could be, its geometry in South America outlines four distinctive zones of active volcanism from the north to the south along the Andean region:

1. The Northern Volcanic Zone developed along the Cauca and Ecuador segments;
2. The Central Volcanic Zone between southern Peru and Northern Chile;
3. The Southern Volcanic Zone;
4. The Austral Volcanic.

Each volcanic zone has its own peculiarities along the continent with an extension almost more than 8000km with elevation up to 7000 masl (Ramos, 1999). Overall, these zones are known by anomalously high seismic velocities, indicating significant seismic activity (Schellart, 2023).

Homrighausen et al. (2020) affirms that most of the world's active volcanoes are located at divergent (spreading centres) and convergent (subduction zones) plate boundaries, which together account for 90% of global volcanic activity. However, the intraplate volcanism incorporates some of the smallest and largest volcanic events Earth and cannot be successfully explained by a single process or model like the subduction model. This is due to the fact that the most significant intraplate volcanic events in terms of volume are associated with a thermo-chemical anomaly originating from the deep mantle and affecting the base of the lithosphere. This short-lived magmatic activity involves the rapid generation and emplacement of large volumes of magma over a relatively short geological timescale. Overall, considering these processes, it is feasible to conceive a wide accumulation of both volcanic and sedimentary materials, enriching the geological heritage in a relatively short period (Dóniz-Páez et al., 2021).

2.1.1 Tungurahua Volcano Aspiring Geopark (Ecuador)

Location and geological setting

The Tungurahua Volcano Aspiring Geopark is located in South America, in the Western Cordillera of Ecuador, interandean valley, and Eastern Cordillera towards to southern Ecuadorian arc (Figure 4). With a total area of 2,397 km^2, it encompasses the Tungurahua and Chimborazo provinces, as well as the municipalities of Baños de Agua Santa, Patate, and Pelileo in the province of Tungurahua, and Penipe and Guano in the province of Chimborazo. The territory is home to a total of 154,759 inhabitants (GVT, 2023).

Overall, Ecuador is defined by extensive volcanic activity dating back to the Quaternary Period, due to the subduction of the Nazca plate beneath the South American plate, giving rise to the Ecuadorian volcanic arc. This volcanic activity includes 84 volcanoes active during the Quaternary, including 25 actives during the Holocene (Barberi et al., 1988; Hall & Beate, 1991; Hall et al., 2008; Bablon et al., 2019). Among these, eight remain active, with recent eruptions documented at Reventador, Cotopaxi, Tungurahua, and Sangay (IG-EPN, 2024).

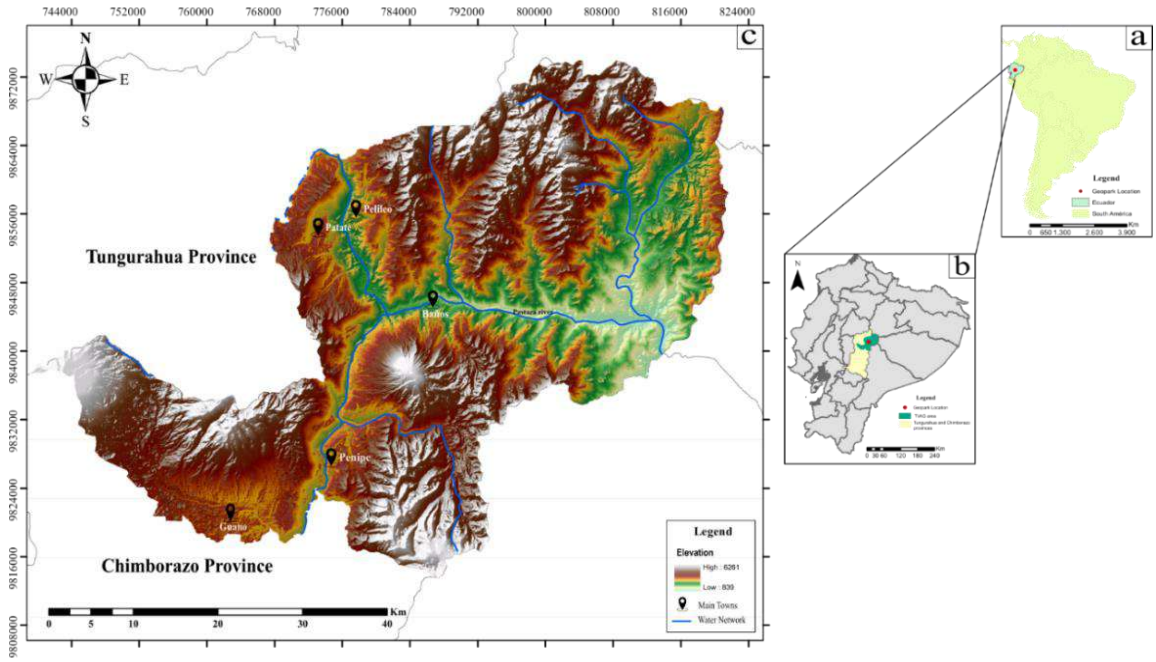


Figure 4. Location and altitude map of TVAG. Source: Adapted from GVT, 2023.

Ecuador's volcanoes are spread across the Western and Eastern Cordilleras, the Interandean Valley, and the back-arc region (Hall & Beate, 1991; Hall et al., 2008). The volcanic arc is 60 to 150 kilometres wide, and mainly stretches northward. However, there are exceptions such as Sangay, Altar, Igualata, and

Tungurahua, which are located in the southern termination of the Ecuadorian Arc (Yepes et al., 2016; Ancellin et al., 2017; Narvaez et al., 2018; Bablon et al., 2019).

The geological Ecuadorian model includes accreted oceanic terranes, which are primarily composed of andesitic to dacitic compound stratovolcanoes at the Western Cordillera. In contrast, andesitic stratovolcanoes are prevalent in the Eastern Cordillera and Interandean Valley. Additionally, Interandean Valley's sections and the Eastern Cordillera comprise Paleozoic to Mesozoic plutonic and metamorphic rocks (Bablon., et al 2019). On the other hand, the back-arc region is characterized by late Cretaceous sedimentary deposits overlying metamorphic rocks and the continental Precambrian craton (Hall et al., 2008).

These accreted oceanic terranes are evident at the Puyo-Baños Corridor in the Baños de Agua Santa canton (Pratt et al., 2005). It reveals significant indicators of geological units, from west to east; Guamote (continental), Alao-Paute (island arc), Loja (continental), Salado (island arc), and Amazonic (continental). The corresponding sutures mark the boundaries between these terranes and are identified as the Peltetec, Baños, Llanganates, and Cosanga faults (Litherland et al., 1994).

According to GVT (2023) the geological evolution of TVAG (Figure 5) is correlated with the terrane model mentioned before (Litherland et al., 1994) spanning from the Lower Devonian to the present. The evolution begins with the Agoyán Unit, representing the Loja terrane, and extends through the Upper Triassic with the Tres Lagunas Granite. Subsequent stages include the formation of the Zamora Batholith in the Lower Jurassic leading to the development of volcanic arcs and terranes. Middle Jurassic events include the formation of the Azafrán Granite unit alongside the Alao volcanic arc, and the introduction of the Maguazo forearc unit in the Upper Jurassic. Transitioning into the Cretaceous, the Peltetec unit emerges, delineating the terrane's tectonic boundary. Miocene volcanic activity forms the Zumbagua Volcanic deposits, followed by the Pisayambo Volcanic deposits in the Pliocene. Pleistocene-Holocene volcanic activity created various eruptive centres at TVAG, including the Chimborazo volcano in the Western Cordillera, the Igualata volcano in the Inter-Andean Valley, the Huisla-Mulmul volcanoes at the western limit of the Western Cordillera, and the Tungurahua and Altar volcanoes at the Eastern Cordillera (Bablon et al., 2019).

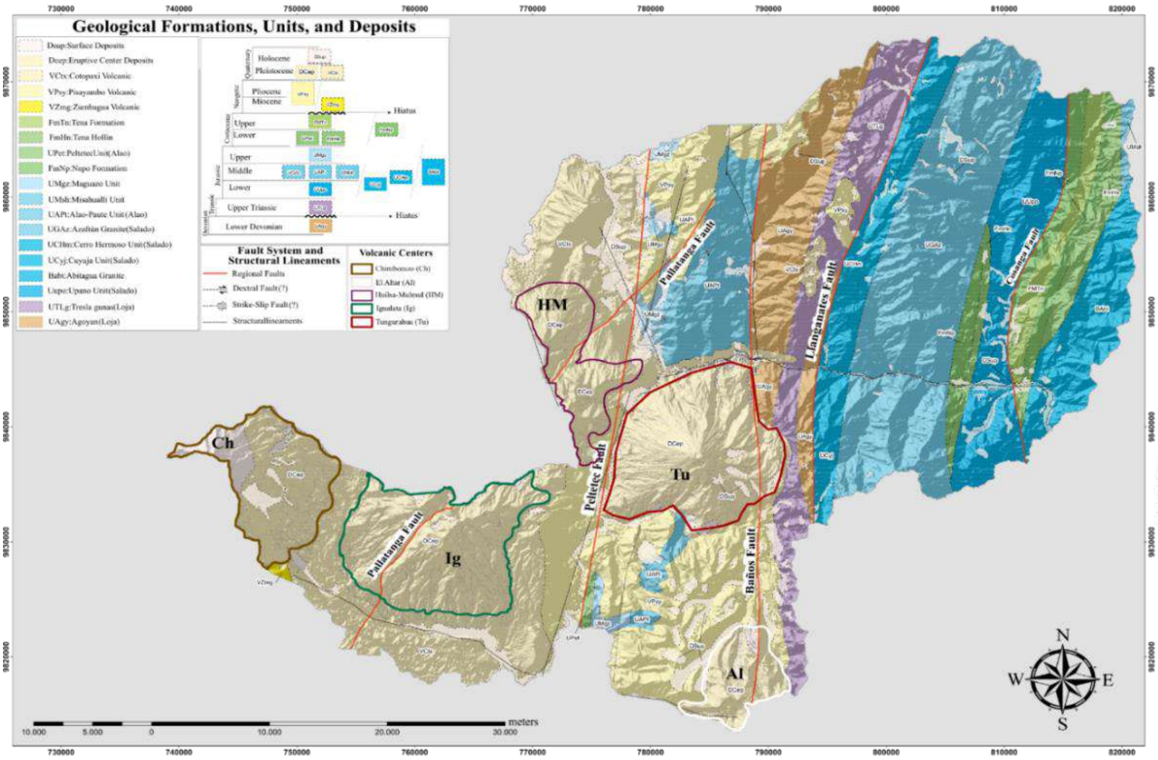


Figure 5. Geological map of TVAG. Source: Adapted from GVT, 2023

Bablon et al. (2019) suggest a probable eruptive history about this set of volcanoes (Figure 6), it can be summarized as follows: The construction of the andesitic Huisla volcano in the Inter-Andean Valley began around 600 ka and ended approximately 500 ka with the emplacement of andesitic domes at the current location of Carihuairazo volcano in the Western Cordillera. Subsequently, Mulmul volcano formed following the sector collapse of Huisla and the large ignimbrite eruption of Chalupas caldera around 215 ka. Igualata volcano began its construction more than 400 ka, with its main edifice completed around 300 ka, coinciding with the onset of Tungurahua's activity in the Eastern Cordillera. Between 300 and 100 ka, volcanic activity increased with the construction of Carihuairazo, Tungurahua, Licto cones, Mulmul volcano, and Puyo cones in the back-arc, as well as the onset of Chimborazo's activity around 120 ka. Finally, the construction of El Altar volcano, located south of Tungurahua, started before 35 ka, marked by significant sector collapses evidenced by debris avalanche deposits, it is important to know there is not enough geochronological information about El Altar eruptive history. These unique geological features provide a general picture of the region's complex geological history.

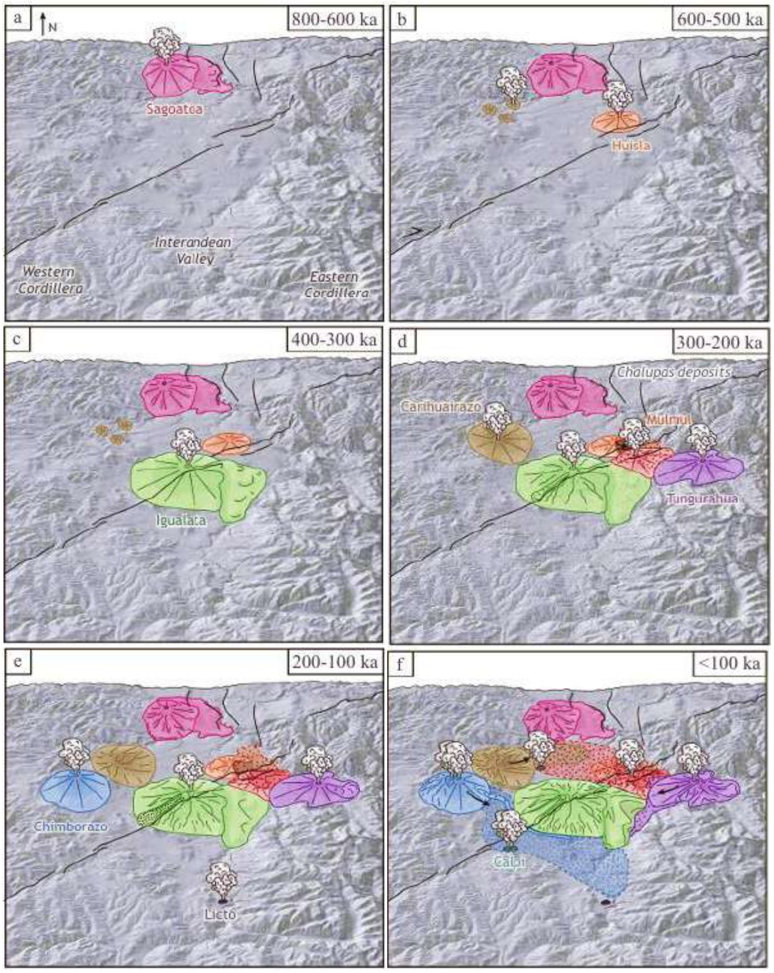


Figure 6. Synthesis of volcanic history of the southern Ecuadorian arc affected by Pallatanga fault. Source: Bablon et al., (2019).

Protected areas and sites

About half of TVAG's territory (54.1%; 2297 km^2) is included in the National System of Protected Areas (SNAP), including Protection of Endangered Forests areas, Private Protection Areas, and water conservation areas. Most of these protected areas are concentrated in the Baños de Agua Santa canton (Figure 7). Water protection areas are mainly present in the cantons of Patate and Pelileo (GVT,2023).

SNAP covers 20% of Ecuador, with 56 nature reserves, three of them are part of the TVAG: Llanganates and Sangay (SNP), and Reserva de proteccion faunistica Chimborazo (SNAP, 2024). In fact, TVAG hosts the Llanganates-Sangay Ecological Corridor (CELS).

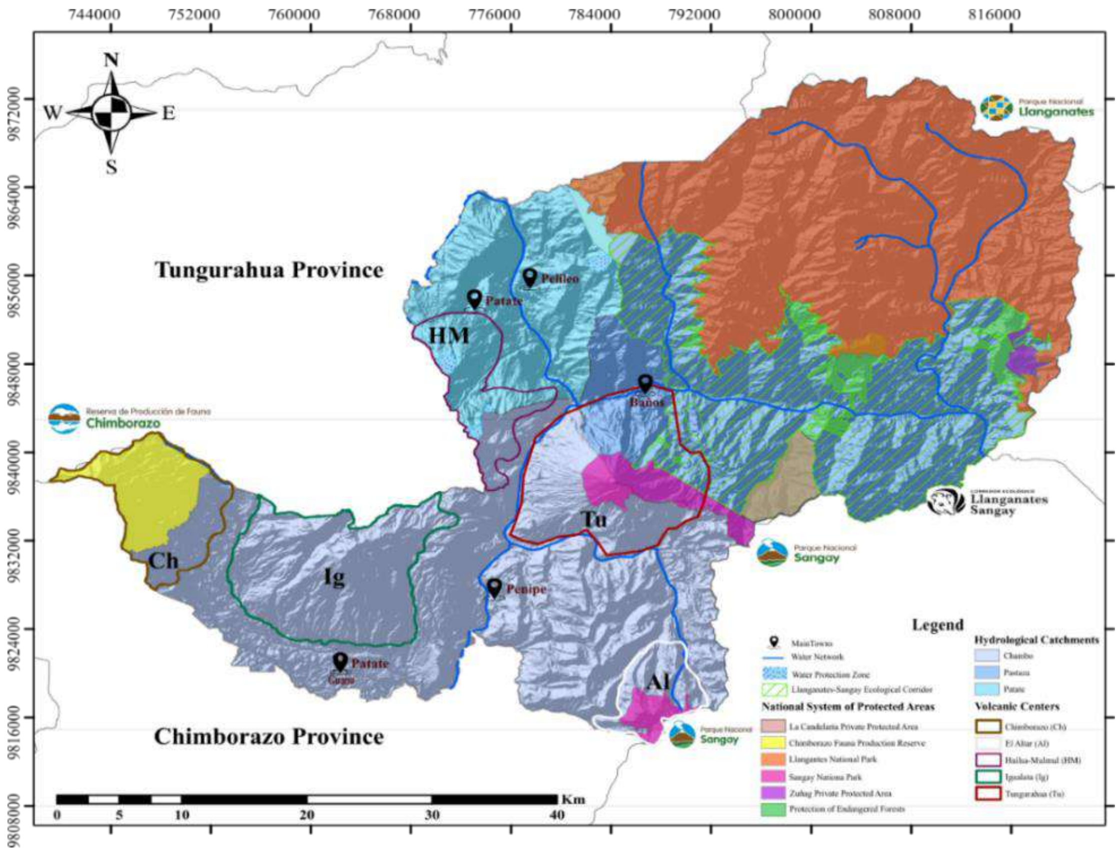


Figure 7. Protected areas in TVAG. Source: Adapted from GVT, 2023.

CELS is part of the Tropical Andes and is considered one of the largest and most biodiverse hotspots worldwide (Myers et al., 2000). It spanning elevations from 760 to 3812 masl and it encompasses a wide range of climatic conditions within a major transition zone between the Ecuadorian highlands and the upper Amazon (Rios-Alvear et al., 2019). The landscape includes human activity, particularly in the urban centre of Baños de Agua Santa Canton, and it is intersected by the Pastaza River, lying between Llanganates National Park (2197 km2) to the north and Sangay National Park (5021 km2) to the south (Rios-Alvear et al., 2019).

Litherland et al. (1994) and Pratt et al. (2005) consider this section the most accessible geological corridor across the Cordillera Western and could be the best section to understand the Ecuador’s geological terrane model. Its unique geographical location and geological history contribute to the high levels of endemism and diverse ecosystems (14 different types) and species (Palminteri et al., 2001; Cuesta et al., 2017, Rios-Alvear et al., 2019) such as the frog of the genus *Pristimantis Tungurahua*, and *Hyloscirtus sethmacfarlanei*. Thus, due to its exceptional biodiversity, role as a refuge from climate change, and potential to link habitats between protected areas, this area was nominated as “Gift to the Earth” by the World Wildlife Fund (WWF) in 2001 (Ríos-Alvear & Reyes-Puig, 2015). In 2023, CELS was formally declared a Connectivity Corridor by the Ecuadorian Ministry of the Environment (Rios-Alvear et al., 2019).

Cultural heritage

The territory includes two ethnic groups of the Kichwa nationality: the Salasakas in Tungurahua Province and the Puruhá in Chimborazo Province (GVT,2023) (Figure 8). Their agricultural practices, using traditional techniques, and their deep respect for nature reflect their connection to the land and environment. Their customs, including celebrations and festivals, are significant pillars that strengthen community bonds and preserve their cultural legacy, featuring traditional dances, music, typical foods, and religious ceremonies (Guevara Moposita et al., 1992). These communities are organized based on principles of solidarity, cooperation, and participation of all members in important decisions, reflecting a united and cohesive community. Music and dance, spiritual worldview, social organization based on reciprocity and collaboration, traditional food, and various annual festivities complete the rich cultural landscape of Indigenous Nationalities of Ecuador in the TVAG. In that sense, the TVAG exemplifies what Sánchez-Cortez (2023) describes: Geoparks in Ecuador are vibrant areas of various heritages, with their true value reflected in the natural elements of the territory, combined with the ancestral knowledge and traditions of the local communities.

The Salasakas (Figures 8a and b) have evolved from diverse origins to become a highly unified ethnic community, believed to have originated from a group of Aymara settlers (Guevara Moposita et al., 1992). They have maintained a specific cultural identity through conscious resistance to colonialism, noted for their pride and strong attachment to their indigenous heritage. In contrast, according to Arevalo (2019), the Puruhá (Figure 8c); d) could not escape the structure of indigenous exploitation introduced by the Spaniards, resulting in the loss of pre-Hispanic culture; however, certain characteristics of their textiles have endured despite attempts at hybridization.

Figure 8. Kichwa nationalities in TVAG: (a) and (b) Salasakas; (c) Puruhás; (d) Baltazar Ushca the last ice merchant of Chimborazo Volcano.

It is important to know that the last ice merchant of Chimborazo Volcano, Baltazar Ushca (Figure 8d), comes from the Puruhá ethnic group. For over half a century, Baltazar Ushca has hiked up the slopes of Chimborazo Volcano. In the past, only 40 Ice Merchants made the journey up the volcano at a time (Casey, 2015). However, Baltazar is now the last one. Currently, he is considered a living heritage in Ecuador (GVT,2023)

2.1.2 Tenerife Island, Canary Archipelago (Spain)

Location and geological setting

Tenerife Island is part of an archipelago located in the centre of the chain of islands that make up the Canary Volcanic Province (CVP) located in the Atlantic Ocean, towards the northwest coast of Africa, specifically near Morocco (Carracedo et al., 2013) (Figure 9). It is the largest and most populated island in the archipelago, with an area of 2034 km2 (Dallavalle et al., 2021), 3718 masl, and a population of 944.107 inhabitants (INE, 2023).

The Canary Volcanic Province is associated to an intraplate volcanism on the African Plate and form a chain 490 km long that ages as it approaches the African continent (Araña & Ortiz, 1991; Carracedo, 2013). Overall, the formation of these islands has been the subject of significant debate (Dóniz-Páez et al., 2020).

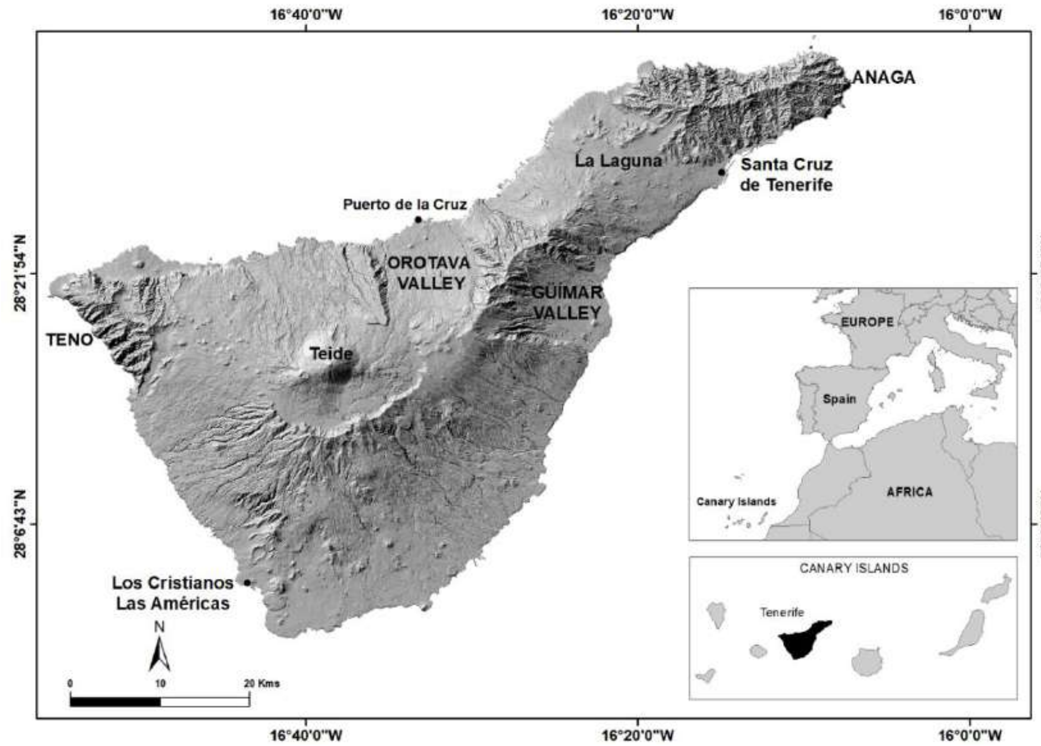


Figure 9. Tenerife Island location map. Source: Adapted from IDE-Canarias (2024).

One theory suggests that the Canary Islands originate from a thermal mantle plume, which minimizes the impact of regional tectonics (Carracedo et al., 1998). Another one emphasizes tectonics as a crucial factor, highlighting the unifying model model (Anguita & Hernán Francisco, 1999) and the uplifted blocks hypothesis (Araña et al., 1991). There are some hypotheses attempt to merge these theories, suggesting the presence of the Morocco microplate (Mantovani et al., 2007), while others support the hot spot hypothesis but also recognize the significance of regional tectonics, particularly related to the Atlas Mountains in Africa (Blanco Montenegro et al., 2018).

According to Romero-Ruiz & Dóniz-Páez (2021), most of the studies agree on the identification of three main volcanic cycles in the Canary Islands:

1. The initial phase of submarine growth, also known as the pre-shield or basal complex phase, which occurred between the Upper Cretaceous and the Miocene. The rocks formed during this phase are visible at the surface only in La Gomera, Fuerteventura, and La Palma islands.
2. Aerial or shield volcanism, which developed mainly during the Miocene and is observable on all the islands except El Hierro, where erosion and accumulation processes predominate over older volcanic deposits.

3. Quaternary subaerial volcanism, present on all the islands except La Gomera. This cycle has given rise to the formation of ridges, volcanic fields, and stratovolcanoes, with volcanic activity recorded since the conquest of the islands.

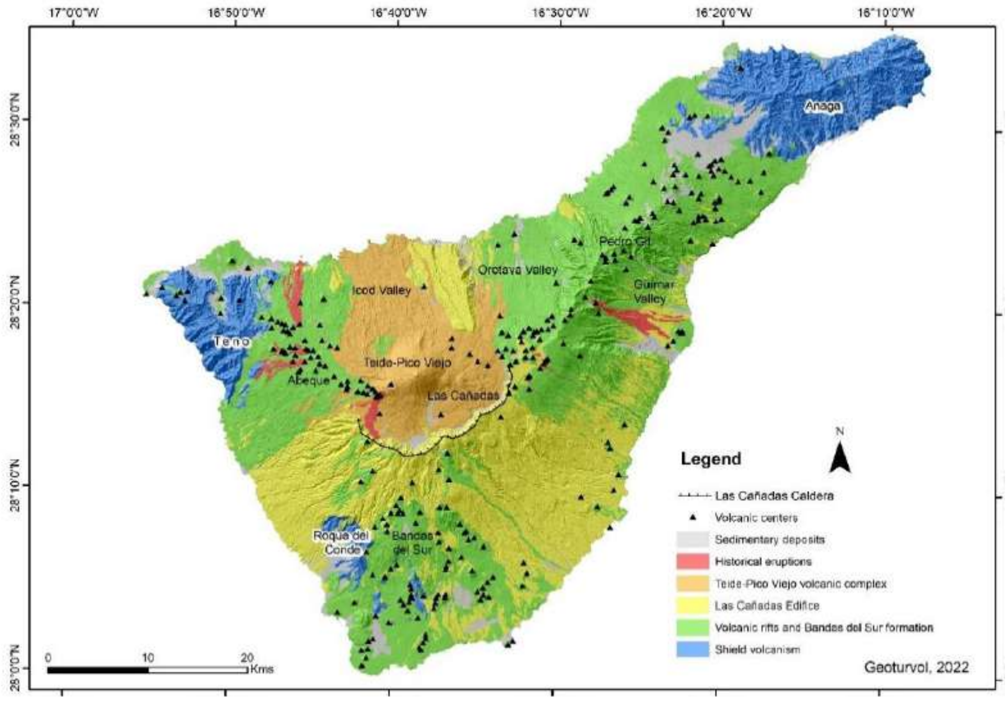


Figure 10. Simplified geological map of Tenerife. Source: Adapted from IDE-Canarias (2024).

Its geodiversity is determined by six different morpho-structural domains (Figure 10): three ancient volcanic structures (Teno, Anaga, and Roque del Conde), two volcanic ridges (Pedro Gil-Orotava-Güímar and Bilma-Abeque), and the Central Edifice with the superimposed Cañadas Edifice (Bandas del Sur) and Teide-Pico Viejo-Icod (Romero-Ruiz et al., 2021).

The volcanic massifs of Teno and Anaga, which date back to the Mio-Pliocene period (6.5-3.5 Ma), are the oldest volcanic formations located at the NE (Anaga) and NW (Teno) ends. The volcanic fields and ridges, such as Pedro Gil and Bilma-Abeque, are volcanic structures formed from numerous monogenetic eruptive episodes during the last 3 Ma (Ancochea et al., 1990). These structures are mainly composed of alkaline basaltic magmas and feature numerous volcanic cones of various morphologies and lava fields (pahoehoe, aa, and lavas blocks) (Romero-Ruiz et al., 2021).

The Central edifice sector includes the Cañadas Edifice and Teide-Pico Viejo edifices, and Icod valley, whose construction spans more than 3 Ma (Ancochea et al., 1990). This sector began with the phonolitic and trachytic volcanism of the Cañadas Edifice and continues to the present with subhistoric volcanic manifestations (Montaña Blanca and Teide Volcanic plug) and historic ones (Chahorra in 1798), featuring up to 20 monogenetic basaltic volcanic cones (Romero-Ruiz et al., 2021).

Protected Natural areas and sites

Tenerife hosts 43 protected areas distributed by 8 categories: National Parks, Integral Nature Reserves, Special Nature Reserves, Nature Parks, Natural Monuments, Rural Parks, Protected Landscape and Site of Scientific Interest (Cabildo de Tenerife, n.d.) (Figure 11).

The Teide National Park (TNP) recognized as the most significant protected area in the Canary Islands, and UNESCO World Heritage site (UNESCO, 2024). It is renowned for three aspects: geology, human use, and vegetation (Dóniz-Páez & Ramírez, 2020).

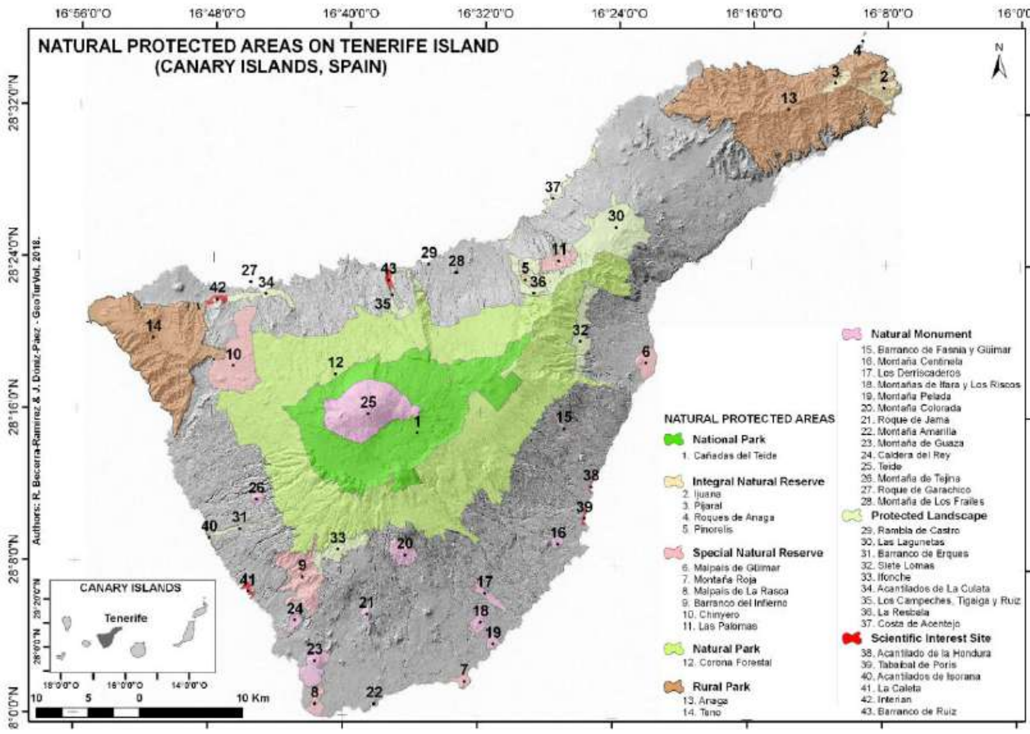


Figure 11. Natural Protected Areas, Tenerife, Canarias, Spain. Source: Adapted from Dóniz-Páez et al., (2018).

Overall, TNP's is noted for its unique volcanic attributes, particularly the Teide-Pico Viejo stratovolcano in the context of intraplate island volcanism worldwide (Carracedo et al., 2007). It is also identified as the highest volcano in the Atlantic and ranks as the third highest in the world when measured from its base on the ocean floor (Carracedo & Troll, 2013). Geologically, it followed three main stages: the formation of the ancient Cañadas Edifice and the emergence of rift volcanism (3Ma, BP); the development of the La Caldera de Las Cañadas, and the Teide-Pico Viejo stratovolcano (0.79 Ma, BP); its development finished with the Narices del Teide historical eruption in 1798 (Martí et al., 1994). These diverse volcanic features and historical eruptions have greatly contributed to its human use and significance, making it the most visited national park in Spain, with annual visitation exceeding three million people (Dóniz-Páez & Ramírez-Becerra, 2020)

The biogeography of TNP has adapted to high subtropical volcanic mountain environments, thus highlighting the different configurations of scrubland. According to Martínez de Pisón et al. (2009), TNP has a high number of endemics species (168 recognized taxa, 58 are Canary endemics, 33 are from Tenerife, and 12 exclusives in TNP. Among the endemic species, the Teide broom (*Spartocytisus supranubius*), red tajinaste (*Echium wildpretii*), and blue tajinaste (Echium *callithyrsum*) stand out, which bloom in spring (Wildpret et al., 2004).

Cultural heritage

The cultural heritage of the Canary Islands has been essential to understand how humans have used this archipelago for centuries; thus, Tenerife Island played a crucial role for the Guanches (Figure 12), the indigenous people in Canary Island, who were unable to resist Spanish colonization and gradually disappeared (Tenerife Weekly, 2024).

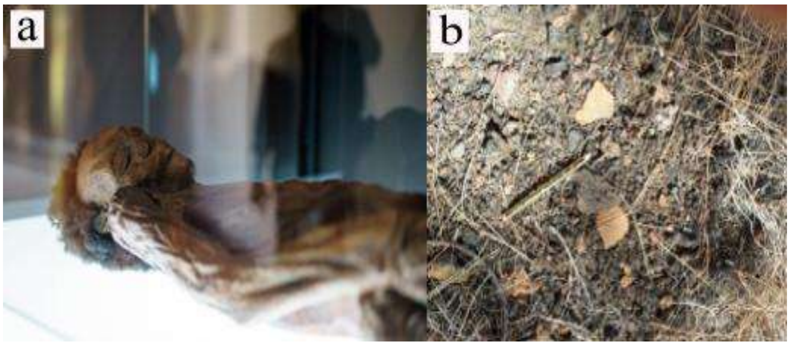


Figure 12. Guanches, the indigenous people in Canary Island. a) Guanche Mummy between 1154-1260; b) Aboriginal pottery remains Teide National Park

Currently, only remnants of this civilization remain, including archaeological remains of cabins, shelters, and pastoral sites with lithic and ceramic utensils (Arnay de la Rosa, 2004). The Teide National Park continues to be a significant attraction for travellers and scientists, influencing the extraordinary geography of myths, legends, traditions, literature, and art (González-Lemus & Sánchez, 2004; Martínez de Pisón et al., 2009; Carracedo & Troll, 2013).

3. RESULTS

In this chapter, we will compare geosites from two different geotectonic contexts: subduction (TVAG) and intraplate volcanism (TI). We are going to provide a comprehensive understanding of the identification, inventory and selection of geosites.

3.1 Geological and geomorphological characterization

According to Rodriguez-Gonzales et al. (2015) results from volcanic activity are influenced by the eruption style (effusive or explosive), the emitted products (lava flows or pyroclastic materials), the viscosity of the magma, and the pre-existing topography. Depending on whether they were formed in a single eruptive event or multiple episodes, volcanic edifices can be classified as "monogenetic" or "polygenetic."

As we can see in chapter 1, the geosites have been grouped according to the geodiversity associated with both volcanic and non-volcanic activity for TVAG and TI, namely volcanic edifices (stratovolcanoes; calderas), eruptive products (lava flows, pyroclastic deposits, and debris avalanches), hydrothermal manifestations (hot springs, travertine formations, and surface manifestations due the tectonic forces), and erosional and depositional products (glacial valleys, erratic fields, nivation hollows, and periglacial structures). These geosites have particular interest for the understanding of the volcanic history for both regions (Dóniz-Páez et al., 2020) and have been linked to their main geological prevailing features (morphological, stratigraphic, tectonic, petrological, and geothermal).

3.1.1 Selection of geosites at TVGA

Overall, we selected five iconic volcanic centres, three lava flows, two pyroclastic deposits, three debris avalanche landforms, two surface manifestations, two lahars and alluvial deposits, and three glacial and periglacial materials. A total of 20 geosites selected in TVAG are represented in Figure 13, and their main characteristics are detailed in Table 4.

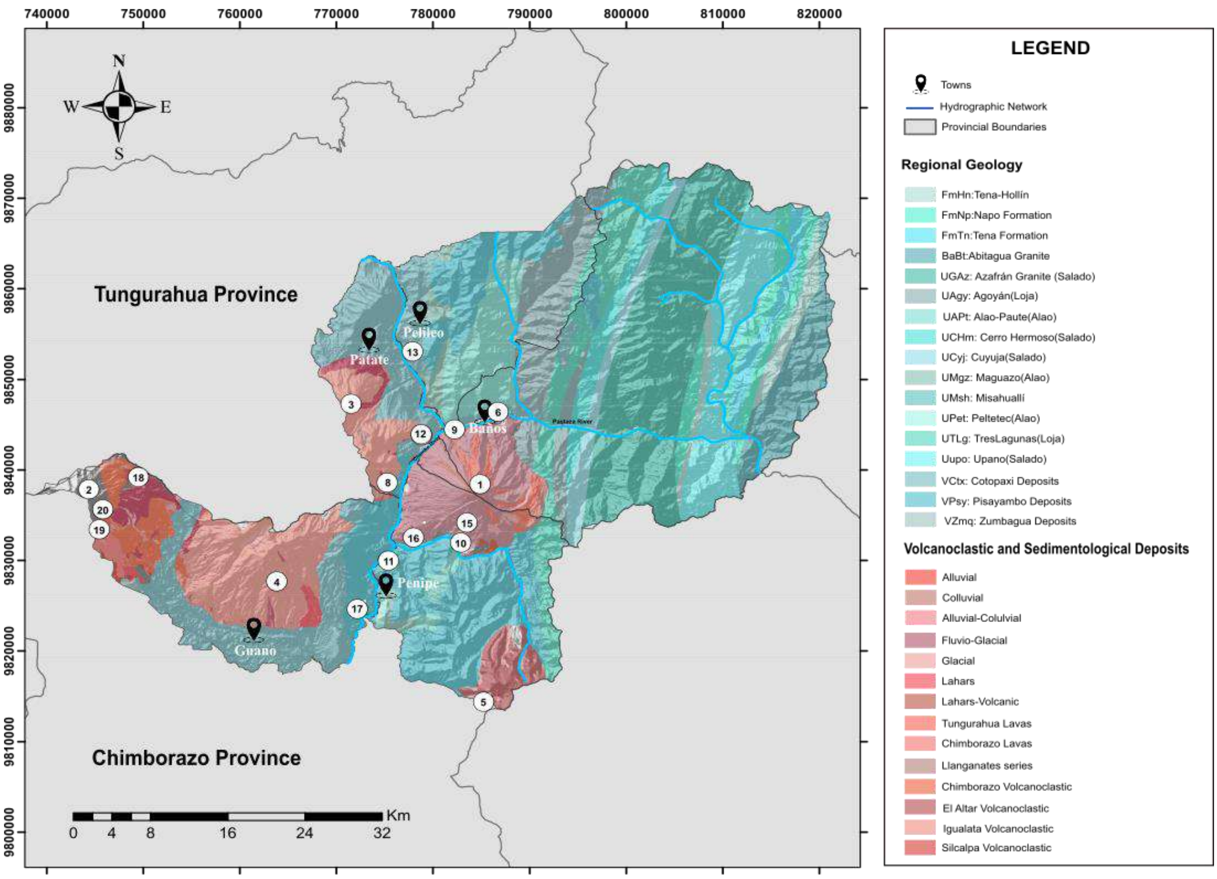


Figure 13. Simplified geological map of TVAG with the location of geosites.

Table 4. General geological and geomorphological description of TVAG's geosites

Volcanic geodiversity	Code	Geosites	Coordinates x	y	General geological and geomorphological description
Composite and stratovolcanoes	TVG01	Tungurahua	784459	9837926	Active between 1999-2016. Three edifices; major collapses around 30 ka and 3 ka BP. Layers: lava flows, pyroclastic flows, lahars, ash, travertine.
	TVG02	Chimborazo	744013	9837359	Three edifices: Whymper, Politécnica, Martínez. Large relief, steep flanks, extensive glaciation.
	TVG03	Huilsla-Mulmul	771137	9846764	Extinct, and eroded, Sector collapses influenced by Pallatanga fault. Extinct, eroded. Mulmul growth within Huisla's collapse amphitheatre.
	TVG04	Igualata	763440	9827209	Eroded and deformed. Summit depression controlled by NE-SW Pallatanga fault.
Craters and calderas	TVG05	El Altar	785898	9815243	Horseshoe-shaped structure from sector collapse. Peaks: El Obispo, La Monja Grande, La Monja Chica, El Tabernáculo, Los Frailes, El Canónigo.
Lava flows	TVG06	Flujo de Lava Baños	786337	9845893	large volume with columnar joints, stratigraphic contact with accreted oceanic terranes, and ancient alluvial terrace
	TVG07	Autobreccia de Bilbao	777800	9839995	Fragmented, non-explosive lava of reddish coloration, exhibiting slab and block structures.
	TVG08	Deformacion Lavica Huilsa-Mulmul	775851	9838702	Deformed by tectonics, yellow alterations (hydrothermal)
PDC	TVG09	Ignimbrita los Pajaros	781846	9843964	Historical Plinian eruption (PDCs)

PFD	TVG10	Cascada de Mayorasgo	782473	9833868	Stratification from multiple eruptive events related with PDCs, PFD, Pyroclastic surges
Debris avalanche	TVG11	Hummocky de Guanandó (30ka)	776547	9831582	Tungurahua II sector collapses (30 ka); irregular hummocky topography, chaotic topography
	TVG12	Hummocky de Cotaló (3ka)	779272	9848200	Tungurahua II sector collapses (3 ka), well-defined conical hills
	TVG13	El templete	777481	9852508	Huisla sector collapses (3 ka), well-defined conical hills, religious significance
Hydrothermal manifestations	TVG14	Las Caras Travertine Deposit	777497	9840531	travertine deposits, petrified roots and fauna, historical significance
	TVG15	Aguas Termales De Puela	783132	9833674	Mesothermal springs, temperatures below 34.3°C, geochemical characterization indicates immature water.
Lahars and alluvial deposits	TVG16	Lahar de San Pedro	779100	9834216	Historical, radial spread from the summit. Composed of gravel in the sandy volcanic matrix.
	TVG17	Depòsito Alluvial de San Miguel	772941	9825505	Alluvial deposit, Periodic mud flows, impact on nearby houses, columnar lavas visible.
Glacial and periglacial materials and landforms	TVG18	Valle Galcial de Abraspungo	750196	9839768	U-shaped and colluvial valley, basal edifices remanent form Chimborazo
	TVG19	Bloques Erraticos del Chimborazo	745077	9834056	Erratic fields, till deposits, Lateral morainic crests
	TVG20	Minas de Hielo Chimborazo	745444	9835134	periglacial zone characterized by cryofracturing and solifluction

Volcanic edifices

Eruptive centres from TVAG's include stratovolcanoes, composite volcanoes, and calderas. These centres are associated with magmas of intermediate to high silica content (andesites, dacites, riolites) (GVT,2023), which, according to Bablon et al. (2019) , have a direct connection with the Chingual-Cosanga-Pallatanga Puná (CCPP) fault system, and especially along the Pallatanga fault segment. These volcanoes exhibit more or less symmetric conical profiles with steep slopes (20-35°) and several kilometres in diameter. Throughout their evolutionary histories, they alternate between effusive and highly explosive phases, as seen in the Tungurahua volcano (Hall et al., 1999).

<u>Stratovolcanoes</u>

Tungurahua volcano was active between 1999 and 2016 (Bablon et al., 2019) It consists of three successive edifices, two of which were partially destroyed by major sector collapses around 30 ka and 3 ka BP, destroying Tungurahua volcanic edifices I and II (Figure 14a.). Its activity began approximately 300 ka, with documented eruptive periods following the Spanish conquest in the years 1640, 1773, 1886, and 1916-1918 AD (Samaniego, 2003).

Figure 14. Volcanic edifices (stratovolcanoes, composite and calderas) at TVAG. a) Tungurahua Volcano; b) Chimborazo Volcanic Complex; c) El Altar; d) Huisla-Mulmul Volcanic Complex; e) Igualata Volcano.

Chimborazo volcano is a potentially active composite volcano (Figure 14b) with an elliptical shape, composed of three successive edifices: "Whymper" (6263 masl), "Politécnica" (5850 masl), and "Martínez" (5650 masl) (Winter et al., 1993). Its eruptive history dating back to 120 ka (BP) (GVT,2023). The ancient Basal Edifice of Chimborazo underwent two main stages of cone construction, known as Abraspungo and El Castillo, followed by dome formation (Samaniego et al., 2012). It is notable for its large relief (2000–3000 meters), steep flanks, and extensive glaciation (Samaniego et al., 2012). Glacial erosion suggests formation predating the Last Glacial Maximum (>33,000 years ago) (GVT,2023).

Calderas

The most prominent volcanic caldera in the TVAG is the eroded andesitic stratovolcano “El Altar” (Figure 14c). According to Bustillos (2008), the caldera, open to the west in a horseshoe-shape structure, formed due to a sector collapse. The peaks of El Altar include six snow-covered peaks exceeding 5000 masl. From south to east and continuing northward, these peaks are: El Obispo (5330 masl), La Monja Grande (5310 masl), La Monja Chica (5154 masl), El Tabernáculo (South 5209 masl), Los Frailes (masl), Central (5125 masl), and El Canónigo (5259 masl). Currently El Altar is hosting “La Laguna Amarilla”.

Regarding the extinct and eroded volcanoes in the TVAG, each has its unique features that tell a story of their past activities. Igualata (Figure 14e), for instance, is an eroded and deformed volcano with flanks affected by deep valleys (GVT,2023). According to Grosse et al. (2020), this volcano has a large depression on its summit oriented from east to west and an elongated pseudo-elliptical base. It is controlled by the NE-SW dextral Pallatanga fault and resembles a pull-apart structure. Mulmul and Huisla volcanoes (Figure 14d), also extinct and eroded, are characterized by sector collapses. The activity of the Pallatanga fault may have triggered these collapses, notably on the southeastern flank of Huisla volcano. As for Mulmul volcano, geochronological data suggest that part of its growth occurred within the sector collapse amphitheater of Huisla volcano (Bablon et al., 2013).

Eruptive products

The eruptive products in the region include lava flows, debris avalanches, and pyroclastic deposits (PDC’s, and PFD) (Figure 15) (GVT,2023)

<u>Lava flows</u>

We selected three lava flows, two from Tungurahua volcano and one from Mulmul-Huisla volcanic complex:

1. Flujo de Lava Baños. Characterized by its large volume and extent, with columnar lavas that exhibit distinctive features, the "Baños Lava Flow" best represents the eruptive power of the Tungurahua volcano. This lava flow is the result of eruptions from the Tungurahua II volcanic edifice, dated to approximately 5000 years BP (Bustillos, 2008), with an andesitic-basaltic composition. It flowed into the valley and began to settle along the course of the Pastaza River. It extends from the Juntas bridge to the Pailón del Diablo waterfall, covering approximately 28 km. This flow formed a plateau on which the urban center of Baños Canton has developed. The flow deposited over parts of the Alao-Paute metamorphic unit section, Azafran Granite (Salado Unit), Tres Lagunas Granite (Loja Unit), Agoyan (Loja), and an ancient

alluvial terrace. This extensive lava flow, characterized mainly by columnar jointing, has been shaped by natural erosion caused by the Pastaza River, resulting in the formation of canyons and waterfalls. Six sites with significant features were selected for study: Las Juntas; San Martin Canyon, San Francisco Bridge, Agoyan Waterfall, Manto de la Novia Waterfall, Pailón del Diablo Waterfall (Figure 15a). To provide a comprehensive overview of the value of this lava flow and correlate it with its sub-geosites, we averaged the data from these six locations and incorporated these values into the overall data for the Baños Lava Flow.

2. Bilbao autobreccia, results from non-explosive lava fragmentation during its flow. It features lava edges in the form of slabs, which form a rigid layer at the lava surface. During the flow's descent, this layer breaks and incorporates into the rest of the lava. The final result is a massive lava flow, red in colour, primarily composed of andesitic and dacitic lava blocks (Figure 15b).
3. At the Mulmul volcano, the outcrop which is showing Mulmul's lavas, is affecting by the region's tectonic activity mainly by Pallatanga fault, present deformations due to tectonic movements and stresses and yellow colour alteration, possibly due to interaction with hydrothermal remnants from the extinct volcano, suggesting the deposition of minerals such as sulphur (GVT,2023) (Figure 15c).

<u>Debris avalanche</u>

The most notable debris avalanches were originated after two collapses on the western flank of Tungurahua II (30 ka and 3 ka) (Bablon et al., 2013; Bustillos et al., 2008, 2013). Another key event was the sector collapse of the extinct Huisla volcano, characterized by rhyolite deposits with irregular structures, and block facies and mixed facies. They exhibit a hummocky topography, with variable and irregular hummocks that are more voluminous and higher in the proximal and middle parts, decreasing in size towards the distal zones (250m of high). It filling up along the Patate and Chambo river valleys, covering approximately 80 km^2 with an estimated volume of 8 km^3, and are visible along the old Baños-Riobamba Road (Hall et al., 1999).

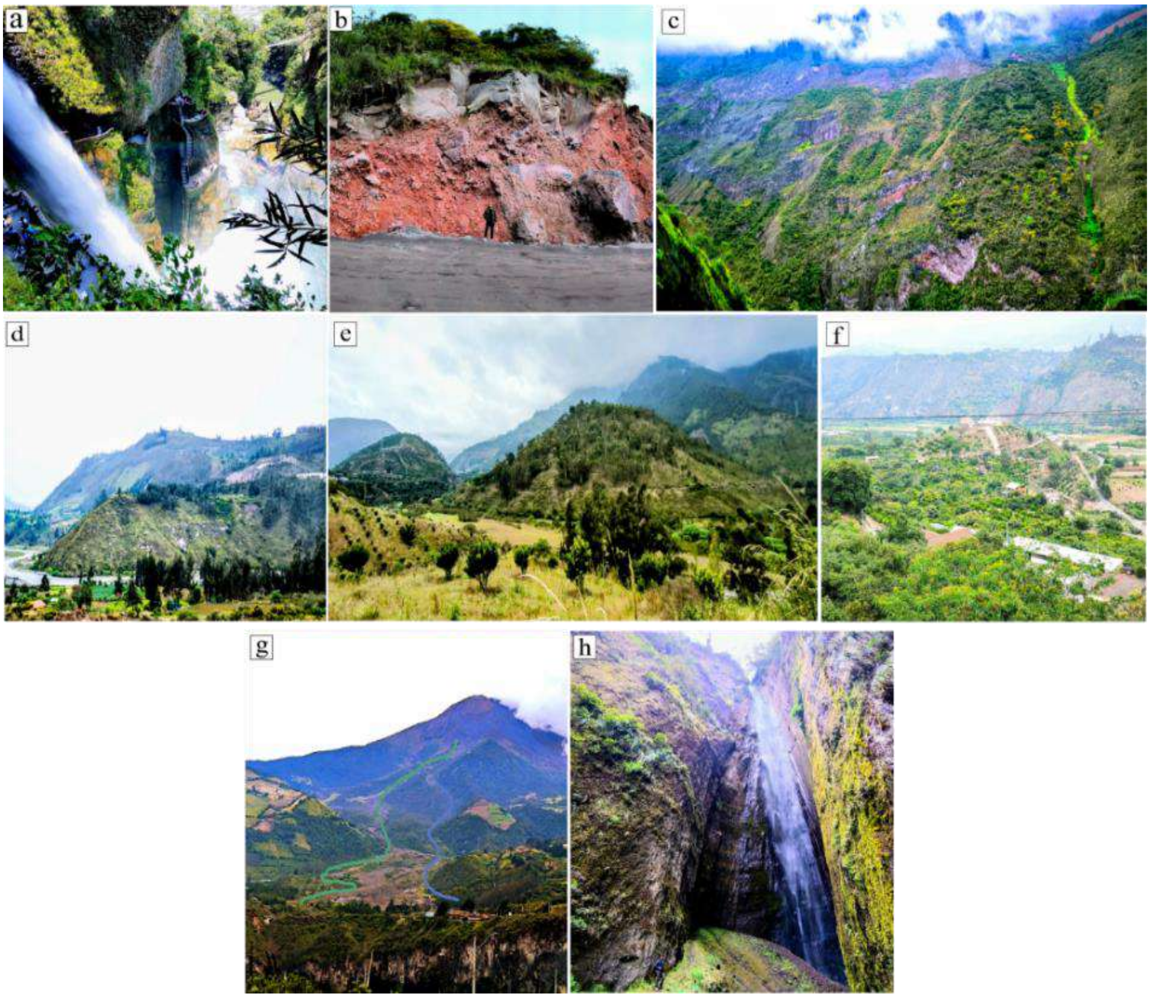


Figure 15. Volcanic products in TVAG lava flows, debris avalanches, and pyroclastic deposits (PDC's, and PFD). a) Pailòn de Diablo; b) Bilbao Autobrecha; c) Huisla-Mulmul deformed lavas; d) Hummocky de Guanandó (30ka); e) Hummocky de Cotaló (3ka); f) El Mirador; g) Ignimbrita Los Pàjaros; h) Cascada Mayorasgo.

For this study, Guanandó Valley part of the Chambo River valley section has been selected to illustrate the hummocky topography of the sector collapse of the Tungurahua II volcanic edifice that occurred 30 ka BP (Figure 15d) (Hall et al., 1999). These deposits form anomalous hills over 150 meters in height, composed of breccias and andesitic lavas, as well as hydrothermally altered rocks in reddish, yellowish, and ochre tones, with subordinate amounts of other altered rocks. The matrix of these deposits is highly consolidated and consists of fine ash with abundant lithic and altered fragments (Hall et al., 1999). However, the most evident hummocky topography is found at Cotaló parish in Pelileo and "El Templete" in the canton of Patate, where the deposits from the lateral collapse of Tungurahua II (3ka) BP (Hall et al., 1999) (Figure 15e), as well as the extinct Huisla volcano can be distinguished (Figure 15f). These hills, relatively small and good sorted distribution, contrast with the chaotic and difficult-to-recognize hummocky topography of the Chambo River section. Overall, they are well-defined conical hills are observed, with heights ranging from 5 to 20 meters, characterized by their symmetrical and conical shape.

Pyroclastic Deposits

We can recognize two volcaniclastic deposits: Los Pájaros Ignimbrite (Figure 15g) and the Mayorazgo waterfall (Figure 15h).

1. Los Pájaros Ignimbrite. It is a pyroclastic density current that was formed due to the Plinian 2006 eruptions from Tungurahua. The flow was channelled and spread towards the north-western flank of the volcano and the Vazcun River valley and inundated topographic depressions up to the E30 road in the Baños de Agua Santa canton. These eruptions, with Volcanic Explosivity Index (VEI) ratings of 2 and 3, generated andesitic pyroclastic flows (GVT,2023). This deposit is composed of plagioclase, clinopyroxene, orthopyroxene, magnetite, and olivine, reached thicknesses of 7 to 10 meters and extends from Juive Grande to Los Pájaros monument.
2. Mayorazgo waterfall, located southwest of the volcano summit on the extinctive Tungurahua I edifice and approximately 70 meters high, exhibits a complex stratification of volcaniclastic deposits. This stratification could be the result of multiple eruptive events that include products from Pyroclastic Density Currents (PDCs), pyroclastic surges, and pyroclastic fall deposits (PFDs), along with debris flow deposits formed by volcanic clasts of various sizes. Some of these deposits have been re-deposited by water currents, reflecting a dynamic interaction between volcanic activity and fluvial processes that have shaped the structure and composition of the waterfall.

Hydrothermal manifestations

1. Deposito de Travertino las Caras (Figure 16a). It is formed over an alluvial terrace related to Pisayambo's volcanic materials and formed from geothermal activity associated with the extinct Mulmul volcano. The residual heat warms groundwater, which cools to around 25°C before emerging. As the water surfaces, calcium carbonate precipitates, forming travertine deposits and petrifying roots and fauna. The site shows significant hydrothermal activity and is connected to ancient civilizations Quillayacus (GVT,2023).

2. Puela Hot Springs (Figure 16b). is located on the southern flank of Tungurahua volcano, these springs feature three natural geothermal pools in the Chambo River sub-basin. Classified as mesothermal springs with temperatures below 34.3°C, they are geochemically characterized by calcium or magnesium bicarbonate ($Mg\text{-}HCO_3$), indicating immature water. This suggests a mix of thermal aquifer water with secondary surface aquifers or meteoric waters heated in the subsurface (GVT,2023).

Figure 16. Hydrothermal Phenomena. a) Depòsito de Travertino Las Caras; b) Aguas Termales de Apuela.

Erosional and depositional products

Erosional and depositional products formed by different geological and climatic processes can be identified: Lahars, alluvial fans deposits, glacial, and periglacial landforms and processes.

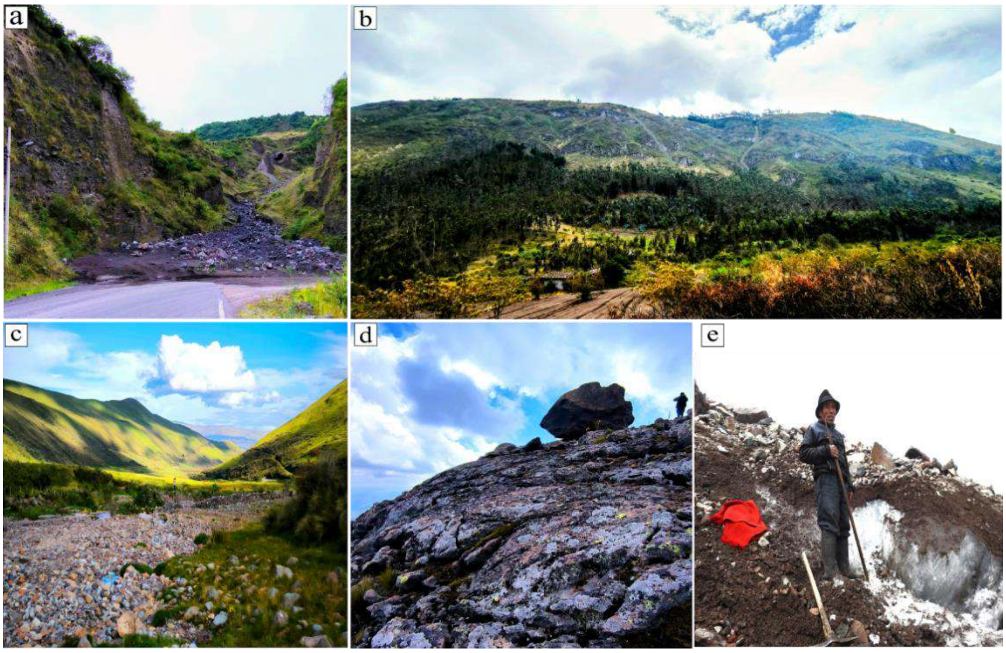


Figure 17. Erosional and depositional products in TVAG. a) Lahar de San Pedro; b) Depòsito Alluvial de San Miguel; c) Valle Glacial de Abraspungo; d) Bloques Erraticos del Chimborazo; e) Minas de Hielo Chimborazo.

Lahars, and Alluvial Deposits

1. San Pedro's lahar (Figure 17a) covers area of 12 ha and has thicknesses ranging from 40 to 100 meters, with moderate slopes. It extends in a radial shape from the volcano summit. This historical lahar caused the disappearance of the main road connecting Riobamba with the Baños canton. The materials composing the lahar include gravels in a sandy volcanic matrix and blocks of andesitic and basaltic composition.
2. San Miguel Alluvial deposit (Figure 17b) is a section of the Igualata volcano where a small alluvial fan has formed. According to villagers, mud flows descend periodically (every 10, 15, or 30 years), causing damage to nearby houses. In the same area, columnar lavas from the Igualata volcano can be observed, where locals have associated with indigenous legends.

Glacial and Periglacial Materials

The Abraspungo glacial valley stands out in the Chimborazo volcano (Figure 17c). It presents a U-shaped valley and a colluvial valley. In this area, the lavas from Basal Chimborazo edifice and the "El Cóndor" waterfall can also be observed. At 4500 masl, along the "Ruta de los Hieleros" (Ice Route), there are glacial erratic boulders up to 5m in diameter, as well as till deposits and glacial moraines (Figure 17d). At nearly 5000 masl, the periglacial zone known as "Minas de Hielo del Chimborazo" or "Los Hielos Eternos del Chimborazo" presents a typical periglacial environment (Figure 17e). This area is characterized by nivation hollow processes, featuring a thick layer of rocks and debris that protects the underlying ice. This phenomenon is attributed to cryofracturing and solifluction processes, which cause movements of soil and debris, burying and exposing the ice, thus creating a dynamic environment, and continuously modifying the landscape.

3.1.2 Selection of geosites at Tenerife Island

Overall, we selected five iconic volcanic centers, three lava flows, two pyroclastic deposits, three debris avalanche landforms, two surface manifestations, one lahars and alluvial deposits, and three glacial and periglacial material deposits. A total of 11 geosites selected in Ti are represented in Figure 18, and their main characteristics are detailed in Table 5.

We made a selection of geosites from Tenerife Island (TI) based on previous works related to geoheritage and geodiversity (Becerra-Ramirez & Dóniz-Páez Javier, 2017; Dóniz-Páez et al., 2020, 2021; Dóniz-Páez

& Ramírez, 2020; Roig Izquierdo et al., 2020). We included sites such as Teide-Pico Viejo volcano, Caldera de las Cañadas, Malpaís de Güimar, among others.

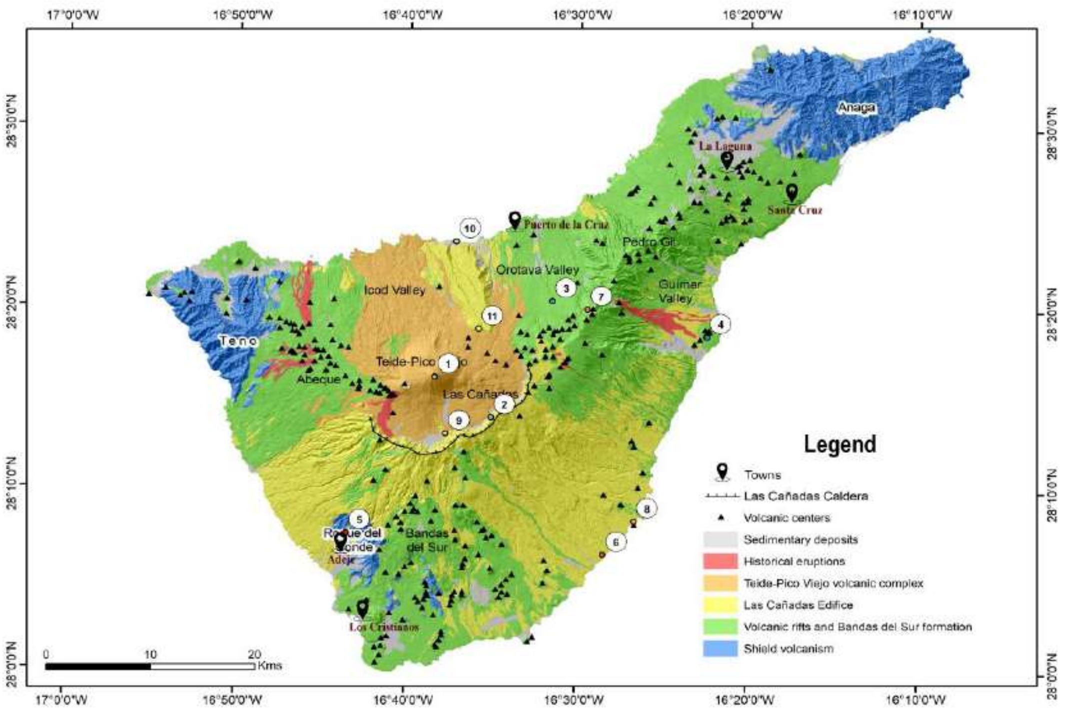


Figure 18. Simplified geological map of TI with the location of geosites.

Overall, we selected the most representative related to volcanic diversity and geodiversity not associated with volcanic activity. A total of eleven representative geosites were selected, as shown in Figure 19 and detailed in Table 5.

Table 5. Geological and geomorphological general description about TI.

Volcanic Geodiversity	Code	Geosites	Coordinates		General geological and geomorphological description
			x	y	
Composite and stratovolcanoes	TI_01	Teide-Pico Viejo	339264	3128210	Polygenetic edifice with stratovolcanoes, strombolian cones, lava domes, and associated lava flows. Features fumarolic activity and glassy phonolite on flanks.
Craters and calderas	TI_02	Caldera de las Cañadas	344647	3124084	Asymmetrical, horseshoe-shaped caldera formed by collapses and sliding. Reflects magmatic evolution and active centre migration
Lava flows	TI_03	Margarita de Piedra	350578	3135890	large volume with columnar joints, stratigraphic contact with accreted oceanic terranes, and ancient alluvial terrace
	TI_04	Malpaís de Güimar	365403	3132205	Holocene lava field associated with 'Montaña Grande' volcano. Features cooling, erosion, and

					sedimentation processes, with a coastal fan of lava flows
	TI_05	Barranco del Infierno	330699	3112385	Steep slopes and a V-shaped channel, basaltic lava flows, altered pyroclasts, trachytic agglomerates, and trachybasalts. Erosional processes, unique hydrogeological springs.
Pyroclastic deposits	TI_06	Ignimbrita de Tajao (PDC)	355368	3110094	Massive and diffusely bedded lapilli. Pyroclastic flow from the Porís de Abona Formation of the Southern Bands resulted from an explosive, caldera-forming phonolitic eruption at Caldera de las Cañadas.
	TI_07	La Tarta del Teide (PFD)	353969	3135108	It records primitive and evolved magmas. Alternation of mafic and felsic pyroclastic deposits, indicating sub-Plinian phonolitic eruptions.
Debris avalanche	TI_08	Abadaes	358337	3113454	Phonolitic eruption recorded 735±5 ka ago, part of Abona Member. Debris-avalanche deposit with block and mixed facies.
Hydrothermal manifestations	TI_09	Azulejos de Ucanca	340294	3122457	Turquoise-blue to pale green rocks formed by hot water ascending through cracks and faults, associated with Llano de Ucanca Caldera edge.
Lahars and alluvial deposits	TI_10	Rambla de los Caballos	341356 .	3142004	Alluvial deposit related to erosional processes.
Glacial materials and landforms	TI_11	La Fortaleza	343482	3133102	Nivation hollows formed by snow erosion, torrential agents, and cryofracturing. Features incipient torrential incisions and well-defined hollows.

Volcanic edifices

Stratovolcanoes

Teide-Pico Viejo (3718 masl) located in the Las Cañadas Caldera (Figure 19a). This complex includes two stratovolcanoes, strombolian cones, lava domes, and associated lava flows. The northern flanks feature more extensive lava flows due to the geometry of the north-facing landslide scar. The central cone has a base diameter of 8 km and steep slopes (20-40°). The volcanic plug at the summit formed after the last major eruption 1,147±140 BP and exhibits fumarolic activity. The flanks are primarily covered by glassy phonolite from the Lavas Negras flows (Ablay & Marti, 2000). Pico Viejo (the secondary volcano) (Figure 20a) on the southwestern flank of Teide, has had recent activity associated with peripheral vents and voluminous phonolitic flows on the northern flank. The magmas involved include phonolite, phonotephrite, and mafic compositions, indicating magma mixing during some eruptions. Erosion has generated periglacial forms and ravines, reflecting a complex geological dynamic of cooling, erosion, and sedimentation. The prehistoric and historic flows on the western and southwestern flanks of Pico Viejo also show intermediate magmatic compositions, indicating a mixture of mafic and phonolitic magmas (Ablay & Marti, 2000).

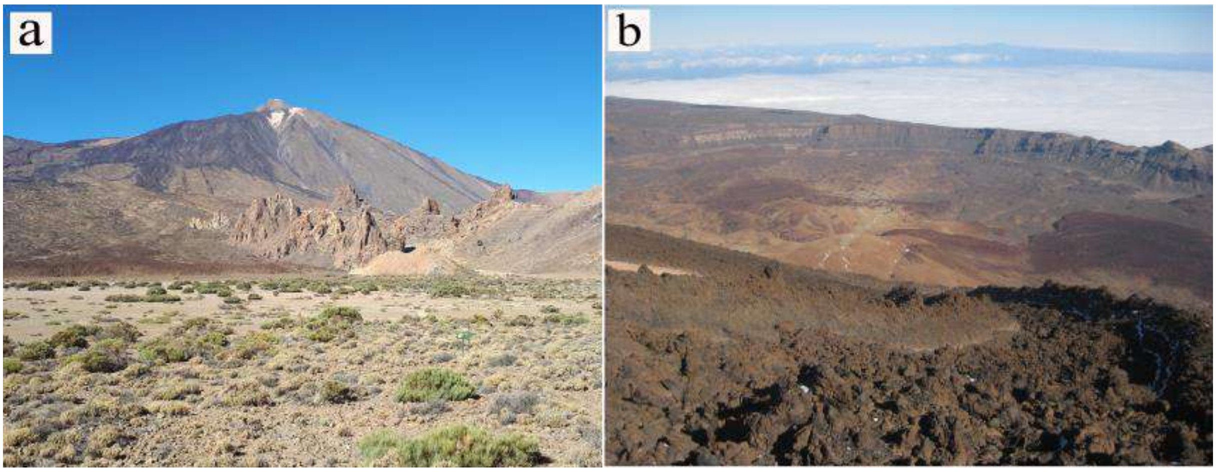


Figure 19. Volcanic Edifices. a) Teide-Pico Viejo; b) Caldera de las Cañadas.

Craters and Calderas

Caldera de las Cañadas. It is an asymmetrical, horseshoe-shaped depression (Figure 19b) 15 km wide and open to the north, resulting from the destruction of the ancient Las Cañadas stratovolcano. Its formation is the subject of several scientific debates. Two hypotheses have been proposed, one suggesting that the caldera was formed by vertical and multiple collapses creating ellipsoidal depressions, recognizing three semi-calderas, and a second one related to a large landslide towards the northern island (Ancochea et al., 1999). In general, the topographic, lithological, and morphological variations of the caldera wall reflect the magmatic evolution and spatial migration of the volcano's active centre related to phonolitic explosive activity cycles (Martí & Gudmundsson, 2000).

Eruptive products

Lava flows

1. The Margarita de Piedra basaltic lava flow (Figure 20a), located in the La Orotava Valley at 1483 masl features structures of radial/cylindrical columnar jointing. It dates back to the Late

Pleistocene, approximately 30 ka, and is associated with the monogenetic Enmedio volcano (Dóniz-Páez et al., 2019).

2. The Malpaís de Güímar lava flow (Figure 20b) is associated with "Montaña Grande" volcano, on the southwestern coast of the Güímar Valley. It is notable for being a well-preserved Holocene lava field of Tenerife, where cooling, erosion, and sedimentation processes can be observed in a coastal volcanic environment. The main emission centre consists of a cone of lapilli, scoria, and basaltic volcanic bombs, and it has a crater 240 meters in diameter. In general, the "aa," "pahoehoe," and blocky lava flows formed a coastal fan. Overall, marine erosion has created an active cliff with cavities and depressions (Di Roberto et al., 2020).
3. Barranco del Infierno (Figure 21c) is characterized by steep slopes and a V-shaped channel. The materials in this area date back 11.86 Ma ago, making it the oldest on the island. It is primarily formed by the Roque del Conde edifice (basaltic, 8.5-12 Ma) and the Cañadas Edifice (1.3-1.9 Ma). The materials found here include basaltic lava flows, altered pyroclasts, trachytic agglomerates, and trachybasalts. Erosional processes affecting the area include torrential flows, slope dynamics, chemical weathering, and anthropogenic effects. This site is significant for its unique hydrogeological springs, known as the Nacientes de Abinque, where the deep multilayer aquifer is drained (Coello et al., 2015).

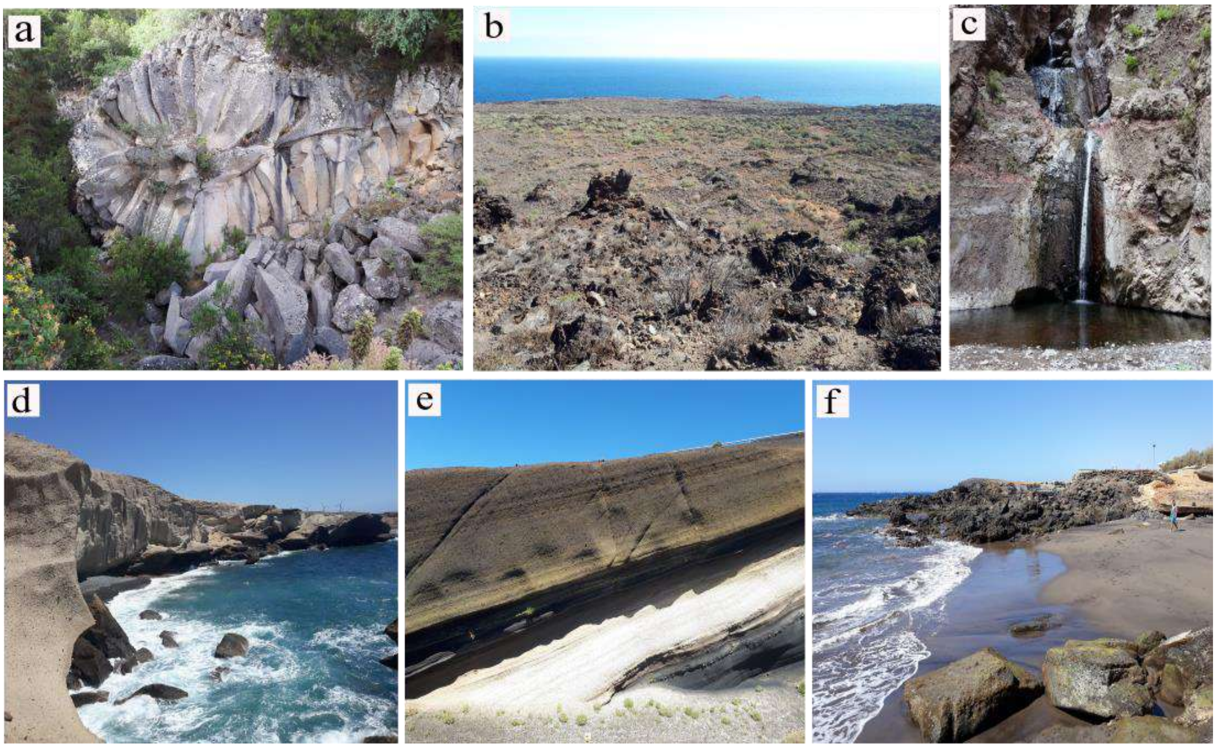


Figure 20. Eruptive Products at TI. Lava flows: a) Margarita de Piedra; b) Malpaìs de Güimar; c) Barranco del Infierno. Pyroclastic Deposits; d) Tajao Ignimbrite; e) Tarta del Teide. Debris Avalanche: f) Playa de Abona.

Pyroclastic Deposits

1. The Tajao Ignimbrite (Figure 20d) is associated with active coastal features connected to Quaternary pyroclastic deposits. These deposits are made up of massive and diffusely bedded lapilli. Specifically, it is a pyroclastic flow from the Porís de Abona Formation of the Southern Bands, which resulted from an explosive, caldera-forming phonolitic eruption at Caldera de las Cañadas 273 ka (Brown & Branney, 2004) . At its base, narrow cords of cobbles and semi-submerged blocks can be seen on the abrasion platform, originating from the collapse of the main front. This ephemeral erosive formation is the result of runoff water undermining a pyroclastic flow of the same formation, displaying an aesthetically valuable arcuate morphology.
2. La Tarta del Teide (Figure 20e), located at the summit of the La Orotava Valley, documents eruptions of both primitive and evolved magmas. It features an alternation of two types of pyroclastic deposits: one mafic, composed of black lapilli and scoria, and the other felsic, consisting of white phonolitic pumice and ash layers. The observed sequence, which shows small settlement faults, indicates the intercalation of a sub-Plinian phonolitic eruption between two fissural basaltic episodes linked to the Northeast Rift Zone. This phenomenon is interpreted as the result of the interaction between a basaltic magma conduit and a shallow phonolitic magma chamber, triggering a highly explosive eruption. At the base, older, reddish, and altered, is impermeable and has given rise to a small aquifer (Carracedo, 2008).

Debris avalanche

Playa de Abona (Figure 20f) is related to the eruptive history of La Caldera de las Cañadas (1.8 to 0.7 Ma) and the Abona Debris Avalanche. It is recording a phonolitic eruption 735 ± 5 ka ago, and is part of the Abona Member. This member spans 90 km² in south-eastern Tenerife, with notable exposures near Vilaflor (1250 masl), Pino del Guirre and Las Vegas (900 masl), and along the coast at Punta Negra. The debris-avalanche deposit lies between pyroclastic units of the Helecho Formation and represents a single eruptive event. It is characterized by block facies and mixed facies, remnants of a hummocky paleotopography with perched lakes, and pervasive fracturing and brecciation (Edgar et al., 2002).

Hydrothermal manifestations

Azulejos de Ucanca (Figures 21a and 21b) are surface manifestations of underlying tectonic forces at Ucanca Azulejos. These turquoise-blue to pale green rocks are found at the base of the Ucanca Edifice wall, near Roques de García in Teide National Park. The cracks and faults through which hot water ascended appear to be associated with the edge of the Llanos de Ucanca Caldera.Erosional and depositional products (Galindo et al., 2005).

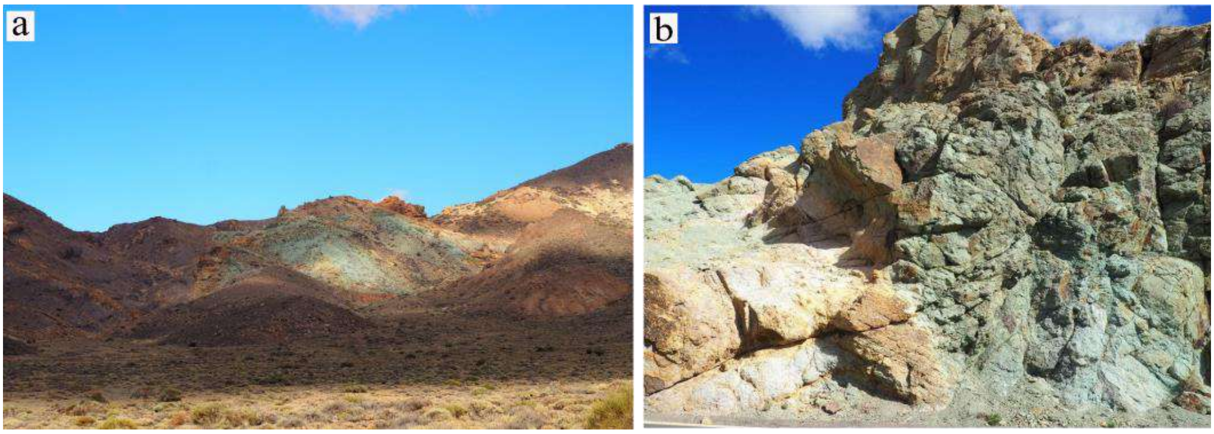


Figure 21. Hydrothermal manifestations in TI. a) Azulejos de Ucanca panoramic view; b) Azulejos de Ucanca outcrop.

Erosional and depositional products

Lahars, and Alluvial Deposits

Rambla de los Caballos (Figure 22a) is related to alluvial action, it is a volcano-sedimentary cliff that showcases the interaction between volcanic and erosive processes on the northern slope of the Cañadas Edifice, and sea-level changes during the Quaternary. This site features 100 m thick alluvial deposits accumulated on top of submarine volcanic rocks, trachybasalts, and phonolites, interbedded with salic tuffs and ignimbrites. The Pliocene outcrops at Las Aguas beach exhibit pillow structures and hyaloclastite breccias, while the submarine lava flows alternate between fragmentary units and massive lavas with columnar jointing. Additionally, remnants of an elevated beach 7-8 m above the current sea level are observed, formed by blocks and pebbles cemented by coastal sands (Galindo et al., 2005).

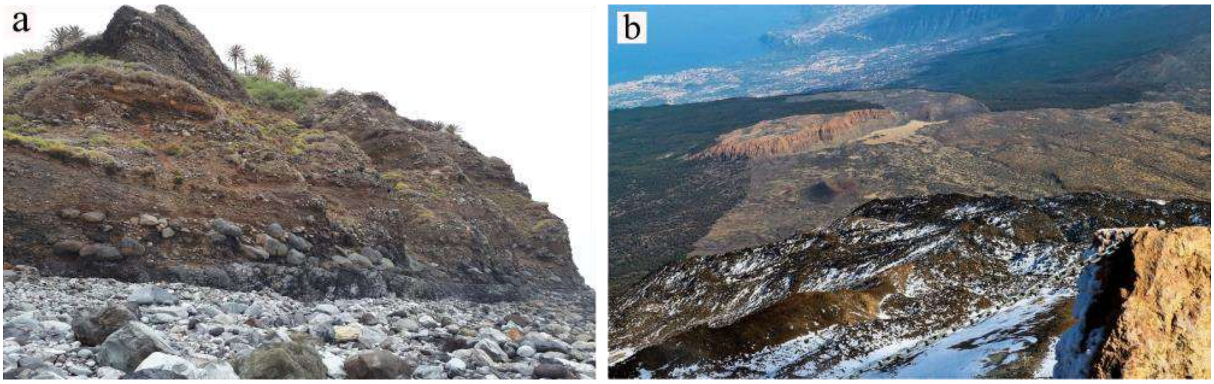


Figure 22. Erosional and depositional products. a) Rambla de los Caballos; b) La Fortaleza.

<u>Glacial and Periglacial Materials</u>

Periglacial processes occur at the high altitudes of Teide volcano, where the soil remains frozen for 3 to 11 months each year near the summit. La Fortaleza nivation hollows (Figure 22b), resulting from The Little Ice Age in the High Teide, are located to the NNE of the Caldera de las Cañadas action (Moreno, 2010). They are structured into two sectors: a lower one with columnar jointing and an upper one, eroded and slightly set back. In the upper sector, incipient torrential incisions and the action of cryo-fracturing can be observed, along with well-defined hollows identified as nivation niches. These niches are evenly distributed along the wall, focusing in the upper part of the escarpment, where the massive lava resists erosion. The nivation hollows in La Fortaleza are formed by the combined action of snow erosion, torrential agents, and cryo-fracturing, reflecting a complex process with repeated phases of snow action (Moreno, 2010).

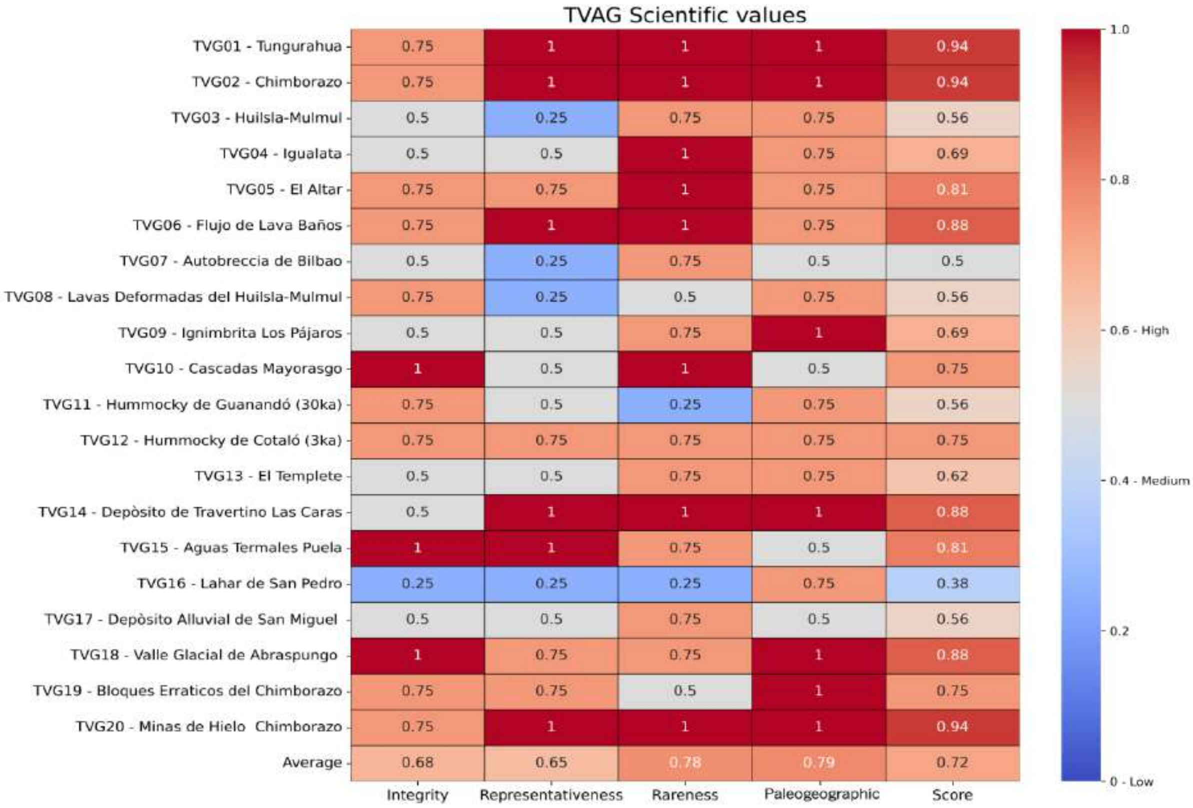
3.2 Geosites assessment

The values/results for both areas regarding scientific values (integrity, representativeness, rarity, integrity) and added values (ecological, aesthetic, cultural, economic) can be distinguished in the heatmaps, Figures 23 and 24 for TVAG, and Figures 25 and 26 for TI. The analysis of the global values for these two areas is shown in Table 6.

3.2.1 Assessment of TVAG's geosites

The analysis of the scientific value reveals that 40% of the TVAG's volcanic edifices present high scores in almost all criteria, including representativeness, rarity, and paleogeographic interest. Notable examples are the TVG0, and TVG02. However, their integrity shows high scores of up to 0.75. Still, it does not reach the maximum value of 1 due to recent eruptions of Tungurahua and the glacial retreat of Chimborazo's ice cap.

Another geosite that presents high values in most categories is TVG20, belonging to the subcategory of glacial and periglacial materials. Similarly, another notable geosite is the TVG15, which belongs to the group of hydrothermal manifestations and shows high levels with a value of 0.88. In contrast, locations such as TVG16 and TVG07, belonging to the groups of erosional products and lava flows respectively, present lower scores (0.38 and 0.5, respectively). Among the geosites studied, 70% (14 geosites) have a global average higher than 0.6, while 30% (6 geosites) have a global average lower than 0.6.



	Integrity	Representativeness	Rareness	Paleogeographic	Score
TVG01 - Tungurahua	0.75	1	1	1	0.94
TVG02 - Chimborazo	0.75	1	1	1	0.94
TVG03 - Huilsla-Mulmul	0.5	0.25	0.75	0.75	0.56
TVG04 - Igualata	0.5	0.5	1	0.75	0.69
TVG05 - El Altar	0.75	0.75	1	0.75	0.81
TVG06 - Flujo de Lava Baños	0.75	1	1	0.75	0.88
TVG07 - Autobreccia de Bilbao	0.5	0.25	0.75	0.5	0.5
TVG08 - Lavas Deformadas del Huilsla-Mulmul	0.75	0.25	0.5	0.75	0.56
TVG09 - Ignimbrita Los Pájaros	0.5	0.5	0.75	1	0.69
TVG10 - Cascadas Mayorasgo	1	0.5	1	0.5	0.75
TVG11 - Hummocky de Guanandó (30ka)	0.75	0.5	0.25	0.75	0.56
TVG12 - Hummocky de Cotaló (3ka)	0.75	0.75	0.75	0.75	0.75
TVG13 - El Templete	0.5	0.5	0.75	0.75	0.62
TVG14 - Depòsito de Travertino Las Caras	0.5	1	1	1	0.88
TVG15 - Aguas Termales Puela	1	1	0.75	0.5	0.81
TVG16 - Lahar de San Pedro	0.25	0.25	0.25	0.75	0.38
TVG17 - Depòsito Alluvial de San Miguel	0.5	0.5	0.75	0.5	0.56
TVG18 - Valle Glacial de Abraspungo	1	0.75	0.75	1	0.88
TVG19 - Bloques Erraticos del Chimborazo	0.75	0.75	0.5	1	0.75
TVG20 - Minas de Hielo Chimborazo	0.75	1	1	1	0.94
Average	0.68	0.65	0.78	0.79	0.72

Figure 23. Scientific value of geosites in TVAG.

Regarding additional values the data underscores significant distinctions for TVG01, TVG02, and TVG05, which belong to the subcategory of stratovolcanoes and calderas; TVG06, which falls under the subcategory of lava flows; and TVG15, classified under surface manifestations. These geosites constitute 25% of the sites, with scores exceeding 0.6. In contrast, the lowest scores are recorded for TVG03, within the subcategory of stratovolcanoes; TVG07 and TVG08, both under lava flows; TVG11 and TVG12, categorized as debris avalanches; and TVG16 and TVG17, pertaining to lahars and alluvial deposits. These sites represent 25% of the geosites with scores below 0.4.

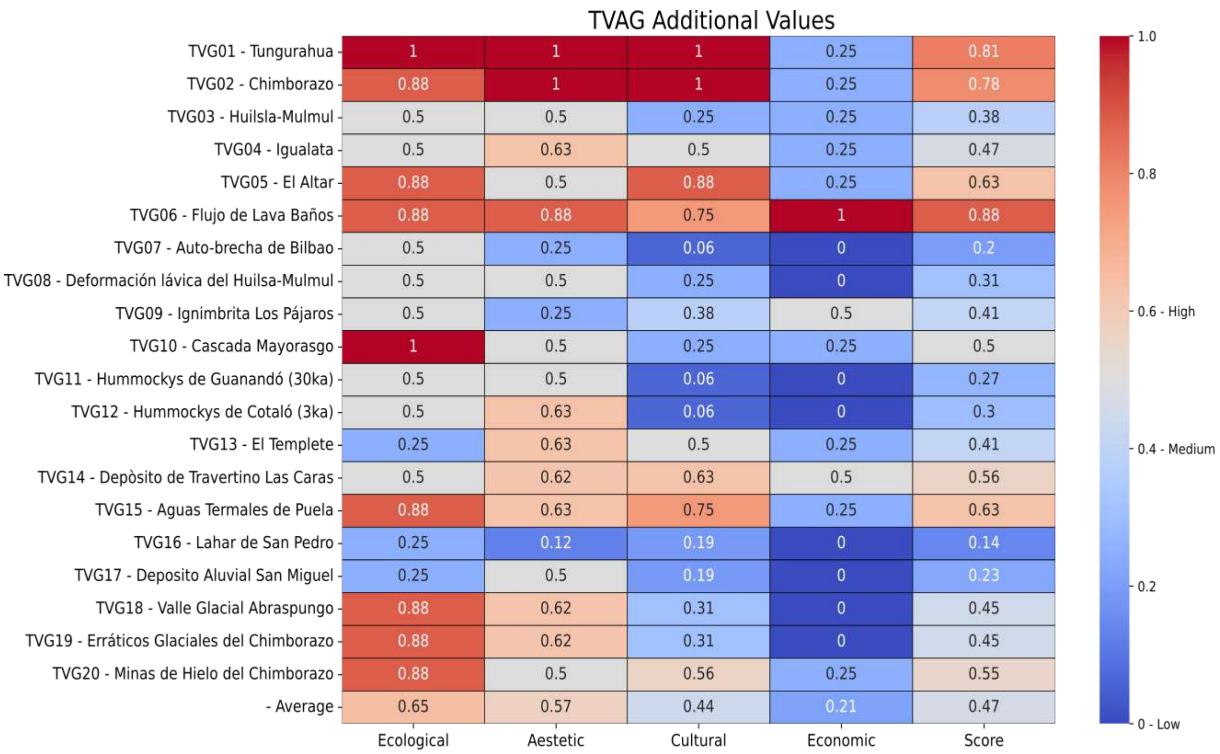


Figure 24. Additional values of geosites in TVAG.

3.2.1 Assessment of TI's geosites

The analysis of the scientific values of the geosites in Tenerife reveals that TI01, TI02, and TI05 stand out with perfect scores (1.0). Both TI01 and TI02 belong to the group of volcanic edifices, representing 100% of the volcanic edifices selected with a perfect rating. On the other hand, TI05, which falls under the subcategory of lava flows within the category of eruptive products, is the only geosite with a perfect score (1.0). It is followed by TI07, which has medium-high values (0.81). Together, TI05 and TI07 represent 33% of the geosites with high values within the eruptive products group, in contrast to the 66% of geosites in this group that do not reach high values. Another geosite with high values is TI09 (0.88), belonging to the hydrothermal manifestations. In contrast, TI03 has the lowest score (0.44), also being in the lava flows subcategory within eruptive products, suggesting a lower value in the evaluated categories (Figure 25).

In terms of additional values (Figure 26), TI01, TI02, and TI05, which fall under the subcategories of stratovolcanoes, calderas, and lava flows respectively, stand out with high scores, collectively representing

27% of the total. Conversely, TI03, categorized under lava flows, and TI06 and TI07, classified under debris avalanches, exhibit low scores, accounting for 45% of the total.

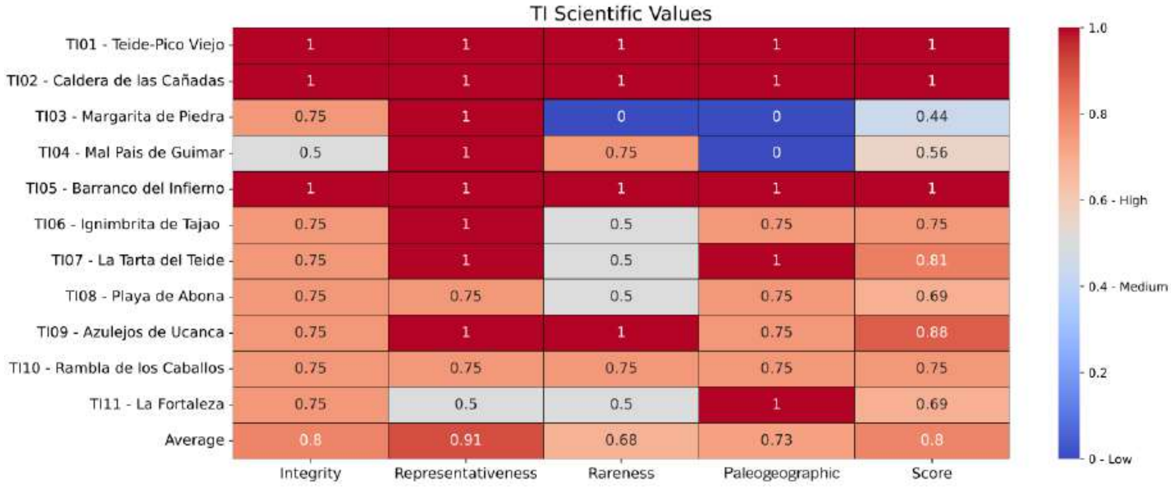


Figure 25. Scientific value of geosites in TI.

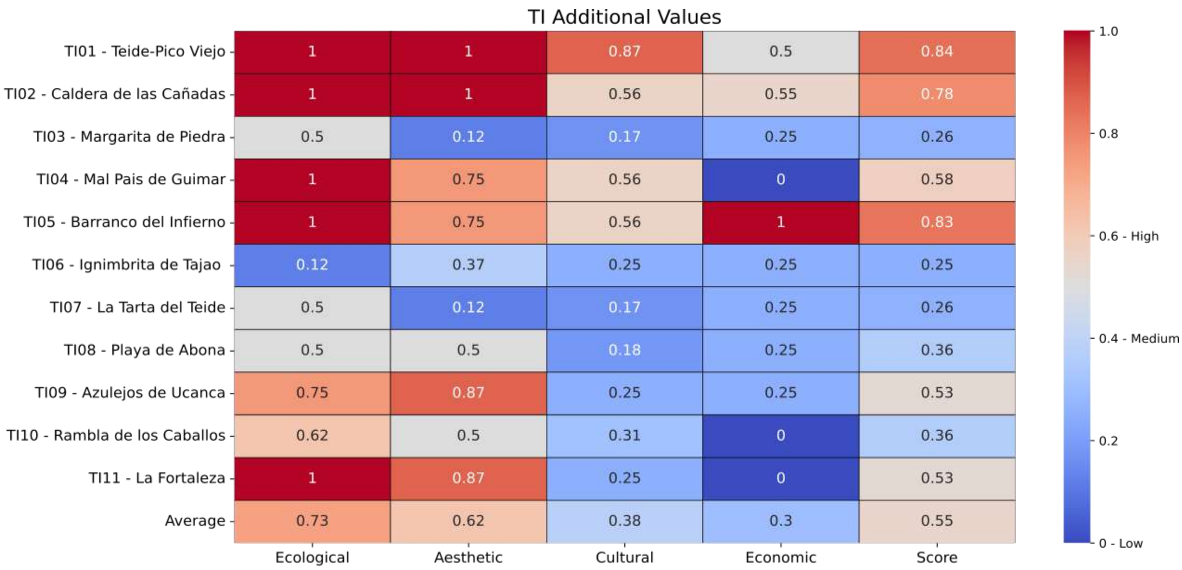


Figure 26. Additional values of geosites in TI.

4. DISCUSSION

Considering that 20 geosites were selected for TVAG and 11 for TI, weighted averages were calculated among the subgroups mentioned in Chapter 1, allowing for an equitable comparison between TVAG and TI, facilitating the identification of differences both scientific and additional values. Global results shows that scientific values are generally higher than additional values (Table 6). Overall, the region that presented the highest values was TI, both in scientific and additional both TVAG and TI, particularly excelling in the integrity criterion of scientific values. However, in terms of additional values, TVAG showed better results than TI in terms of cultural criteria.

Table 6. Scientific and additional Global values in TVAG and TI

Volcanic diversity (TVAG / TI)		**Tungurahua Volcano Aspiring Geopark (TVAG)**			**Tenerife Island (TI)**		
		Name	**Global Scientific Value**	**Global Additional value**	**Name**	**Global Scientific Value**	**Global Additional value**
Volcanic edifices	Stratovolcanoes	Tungurahua	0,938	0,813	Teide-Pico viejo	1	0,84
		Chimborazo	0,938	0,781			
		Huisla-Mulmul	0,563	0,375			
		Igualata	0,688	0,469			
	Calderas	El Altar	0,813	0,625	Caldera de las Cañadas	1	0,78
Eruptive products	Lava flows	Flujo de Lava Baños	0,875	0,875	Margarita de Piedra	0,44	0,26
					Malpais de Guilmar	0,56	0,58
		Autobrecha de Bilbao	0,5	0,203	Barranco del Infierno	1	0,83
		Deformacion Lavica Huisla-Mulmul	0,563	0,313			
	Pyroclastic Deposits	Ignimbrita de los Pájaros	0,688	0,406	Tajao	0,75	0,25
		Cascada de Mayorasgo	0,75	0,5	Tarta del Teide	0,81	0,26
	Debris avalanche	Hummocky de Guanandó (30ka)	0,563	0,266	Abadaes	0,69	0,36
		Hummockys de Cotaló (3ka)	0,75	0,297			
		El templete	0,625	0,406			
Hydrothermal	Surface manifestation	Depósito de Travertino Las Caras	0,813	0,563	Azulejos de Ucanca	0,88	0,53
		Aguas Termales de Puela	0,875	0,626			

Erosional and depositional	Lahars, and alluvial deposits	Lahar de San Pedro	0,38	0,14	Rambla de los caballos	0,75	0,36
		Deposito Aluvial San Miguel	0,56	0,23			
	Glacial and periglacial materials and landforms	Valle Glacial Abraspungo	0,88	0,45	La forteza	0,69	0,53
		Erráticos Glaciares del Chimborazo	0,75	0,45			
		Minas de Hielo del Chimborazo	0,94	0,45			

4.1 Comparing geosites from TVAG and TI

Analysing the subgroups mentioned in Chapter 1, TI geosites present higher values, especially in stratovolcanoes and calderas, where TI showed elevated values in the criteria from scientific values (1.00 in both criteria) (Table 7 and Figure 27).

Table 7. Comparison of Average Geosite Values in TVAG and TI by Geodiversity Criteria.

		Scientific value				**Additional values**			
Volcanic geodiversity	**Region**	**Integrity**	**Representativeness**	**Rareness**	**Paleogeographic interest**	**Ecological**	**Aesthetic**	**Cultural**	**Economic**
Stratovolcanoes	TVAG	0,63	0,69	0,94	0,88	0,72	0,78	0,69	0,25
	TI	1	1	1	1	1	1	0,87	0,5
Craters and calderas	TVAG	0,75	0,75	1	0,75	0,88	0,5	0,88	0,25
	TI	1	1	1	1	1	1	0,56	0,55
Lava flows	TVAG	0,60	0,38	0,60	0,58	0,51	0,46	0,22	0,17
	TI	0,75	1	0,58	0,33	0,83	0,54	0,43	0,42
Pyroclastic deposits	TVAG	0,75	0,50	0,88	0,75	0,75	0,38	0,31	0,38
	TI	0,75	1	0,50	0,88	0,31	0,25	0,21	0,25
Debris avalanche	TVAG	0,67	0,58	0,58	0,75	0,42	0,58	0,21	0,08
	TI	0,75	0,75	0,50	0,75	0,50	0,50	0,18	0,25
Surface manifestation	TVAG	0,75	1,	0,88	0,75	0,69	0,63	0,69	0,38
	TI	0,75	1,00	1,00	0,75	0,75	0,87	0,25	0,25
Lahars and alluvial deposits	TVAG	0,38	0,38	0,50	0,63	0,25	0,31	0,19	0,00
	TI	0,75	0,75	0,75	0,75	0,62	0,50	0,31	0,00
Glacial and periglacial materials	TVAG	0,83	0,83	0,75	1,00	0,88	0,58	0,40	0,08
	TI	0,75	0,50	0,50	1,00	1,00	0,87	0,25	0,00

High values could be related to the fact that TI01 is a stratovolcano with low volcanic activity. Its last historical eruption was in 1798 (Narices del Teide eruption), allowing the landscape to experience minimal changes recently (Pérez-Umaña et al., 2019). This coincides with Carracedo & Troll (2013), who affirm that the geological stability of the Canary Islands provides an excellent area for long-term volcanic research. Additionally, TI is considered a post-erosional island, meaning it has passed its main volcanic growth stage and is in a phase of reduced volcanic activity (Carracedo and Troll, 2013).

Higher values are distinguished in surface manifestations, like in geosites TI09 and TVG14, in terms of representativeness and rareness. TI09, which is part of the western wall of geosite TI02, reflects the observations of Pérez-Umaña et al. (2019) and Dóniz-Páez (2010). They state that the emitted materials within the boundaries of the TPN allow for the recognition of unique forms and processes directly related to TI eruptive phenomena in a relatively small area. Regarding TVG14, its rareness values could be related to the fact that it is a trace of ancient Indigenous communities, plus the fact that the spot is a hot spring (GVT, 2023). Thus, the combination and preservation of these diverse geological elements in a single location are what makes geosites like TI09 and TVG14 both representative and rare.

On the other hand, TVAG lower values in terms of integrity (0.63) and representativeness (0.69) in stratovolcanoes and calderas compared to TI, presents a different but equal picture. According to IG-EPN (2024), TVG01 has shown volcanic activity since 1300 AD. Thus, it has produced eruptions with pyroclastic flows, ash falls, lava flows, and lahars at least once per century (Le Pennec et al., 2008), recording volcanic explosivity indices (VEI 2-3) with its last eruptions in 2016 (IG-EPN, 2024). These eruptions have caused severe damage to surrounding cantons such as Pelileo, Baños, and Penipe (GVT, 2023). Overall, the frequency and magnitude of eruptions in TVAG and TI over time reveal that Tungurahua has experienced 17 eruptive periods since 1534, five of which were significant in magnitude (VEI 3-4) during the years 1641-1646, 1773-1781, 1886-1888, 1916-1918, and 1999-2016 (Samaniego,2003). In comparison, Teide has remained relatively calm since its last eruption in 1798 (Medieval Period) (Dóniz-Páez, 2015); these differences in recent and past volcanic activity have directly influenced the observed values of integrity and representativeness in both regions.

In criteria where TVAG showed relatively high values, they are related to representativeness and rarity in glacial and periglacial materials. Periglacial materials show higher representativeness (0.83 vs. 0.50 in TI) and rarity (0.75 vs. 0.50 in TI), which could be linked to more stable climatic conditions and less extreme variations in TVAG. For example, the geosites in this subgroup are mostly located on the

Chimborazo Volcano, one of the largest ice-covered volcanic complexes in the northern Andes (Clapperton, 1990). In comparison, the Teide-Pico Viejo stratovolcano, according to Hernández (2012), only after heavy rains or the melting of winter snow do the soils and rocks become sufficiently moist to freeze. Additionally, the observed characteristics at the TVG20, with nivation and cryo-weathering processes, as well as the presence of erratic boulders and moraines, are typically frequent in regional insular contexts. In TI, periglacial processes, although present, are less exceptional due to climatic factors that limit their occurrence to winter seasons.

TVAG stands out in some specific subgroups within the criteria of scientific values such as rareness. TVAG shows higher values in pyroclastic deposits (0.88 in TVAG vs. 0.55 in TI) and lava flows (0.75 vs. 0.58 in TI), which could be related about the volcanic powerful activity typical of a subduction zone. Additionally, the volcanoes in this region have been built on accreted terrains, making them exceptional examples in terms of the extent and frequency of occurrences. Thus, pyroclastic deposits such as the Mayorasgo waterfall exhibit significant complexity. This complexity is not only due to their multiple powerful eruptive events but also to their interaction with hydrological processes, resulting in the creation of unique waterfalls, especially spectacular from a scenic point of view. In this context, Phuong (2016) states that waterfalls represent notable deposits due to their impressive geological object system, which is usually characterized by columnar and pillow lavas. However, the Mayorasgo waterfall is mainly characterized by an exceptional pyroclastic flow deposit. Overall, this deposit is notable not only for its impressive landscape but also for its location in a high ecological value area, such as a primary forest, observed during this master's research fieldwork.

Regarding paleogeographical interest, TVAG shows high values (0.67 vs. 0.33 in TI) in its lava flows, highlighting the importance of these sites for the evolution of the volcanic landscape. Lava flows such as the 'Flujo de lava Baños', a significant eruptive event that has shaped the landscape, creating canyons and waterfalls along the water systems, are of particular interest. This dynamic interaction between lava and fluvial erosive processes offers rich geomorphological evidence. Additionally, the diversity of compositions and structures in Tungurahua, such as andesitic-basaltic lavas with columns and autobreccias in contact with accreted oceanic terrains, explains the record of fundamental tectonic processes in the evolution of continents, adding a layer of complexity to the geological diversity that may influence TVAG. Furthermore, the direct impact of the Baños Lava Flow on human development, forming a plateau on which the urban centre of Baños has developed, adds additional paleogeographical value. In contrast, lava flows in Tenerife, although significant, are more localized and show less extent and volume. Overall, Lava flows in Tenerife, such as the Margarita de Piedra lava flow and the Malpaís de Güímar lava flow, although significant, are more localized and do not reach the same extent and power.

In terms of scientific values, both TVAG and TI coincide in surface manifestations, presenting high values in the criteria of integrity (0.75), representativeness (1.00), and paleogeographic (0,75). In TVAG, the integrity could be to the constant renewal of the landscape, as evidenced in the geosite “Las Caras,” which showed its current characteristics after the volcanic activity of Tungurahua in 2006 (GVT, 2023). In TI, the lower frequency of volcanic activity has allowed hydrothermal manifestations to remain largely unaltered, maintaining their integrity over time. On the other hand, the perfect representativeness (1.00) in both regions indicates that hydrothermal manifestations are outstanding examples of these geological phenomena, reflecting both the geological stability of TI and the dynamic volcanic activity in TVAG.

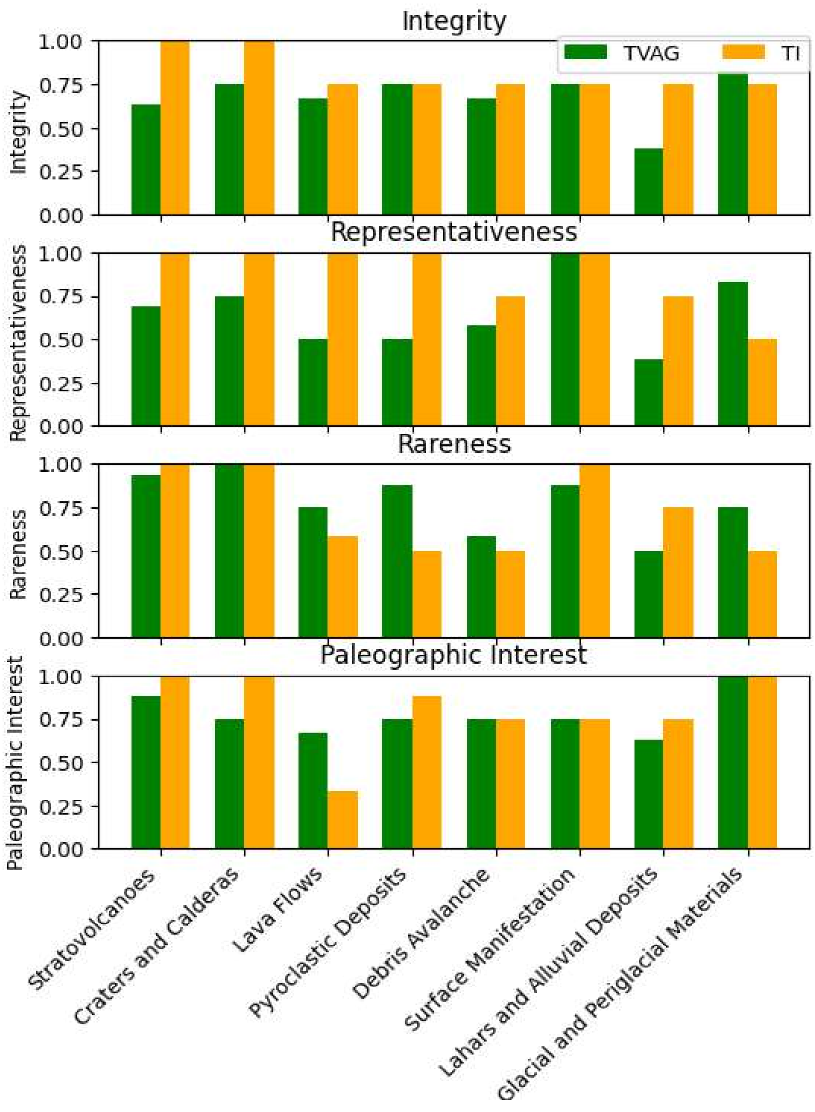


Figure 27. Scientific values vs subgroups selected.

Regarding additional values (Figure 28), TI presents high scores in most of the evaluated criteria, except for the cultural value, where TVAG stands out with a score of 0.50 compared to 0.38 in TI. Concerning ecological criteria, TI stands out notably in the subgroups of stratovolcanoes (1 vs. 0.71 in TVAG), craters and calderas (1 vs. 0.88 in TVAG), and periglacial materials (1 vs. 0.88 in TVAG). These high values are mainly influenced by being in essential areas for ecosystem development. Geosites such as TI01 and TI02 are located in the Teide National Park (TNP), internationally recognized as a UNESCO World Heritage Site (UNESCO, 2024). Although values in TVAG are relatively lower, they remain high; thus, geosites such as TVG01, TVG02, TVG05, and TVG06 are in internationally and nationally protected areas. TVG01, TVG05, and part of TVG06, for example, are within the Sangay National Park (SNP), another natural reserve declared as a UNESCO World Heritage Site (UNESCO, 2024). Overall, the lower values in TVAG can be attributed to geosites such as TVG03 and TVG04, stratovolcanoes that are not within protected areas, suggesting that sample size may have influenced the final value. In fact, Mokkink et al. (2023) found that accuracy improves significantly when the number of samples is increased from 2 to 3. However, while increasing the sample size can enhance the precision of estimates, these increases can also be costly and require more time and resources.

Regarding pyroclastic deposits and lava flows, TVAG shows high values (0.75 vs. 0.32 in TI and 1. vs. 0.83 in TI, respectively), mainly influenced by their location in highly ecological influence zones, such as primary forests and internationally protected national parks (GVT, 2023). In terms of aesthetic values, TI presents high values in stratovolcanoes (1 vs. 0.78 in TVAG), craters (1 vs. 0.78 in TVAG), and periglacial materials (0.87 vs. 0.58 in TVAG). These values could be directly related to accessibility and investment in tourism infrastructure in the TNP, which includes interpretation centres, restaurants, trail networks, cable cars, national lodges, public transport, and parking lots (Dóniz-Páez & Ramírez-Becerra, 2020).

The variety of observation points and the visual contrast of these formations in subtropical environments also contribute to these values. According to UNESCO (2024), the visual impact of a site is largely due to atmospheric conditions that continually modify the textures and tones of the landscape, as well as the impressive spectacle of the “sea of clouds” that forms the backdrop of the mountain. In this same context, TVAG stood out in lava flows (0.88 vs. 0.54 in TI) and pyroclastic deposits (0.38 vs. 0.25 in TI), highlighting the scenic beauty and vertical development of these features in TVAG. Part of these subgroups are within the limits of the NPS, providing an excellent example of continuous succession, where volcanic ash creates fertile soil and new habitats for the development of ecosystems such as tropical forests, cloud forests, grasslands, and paramo vegetation, making TVAG an area of exceptional natural beauty.

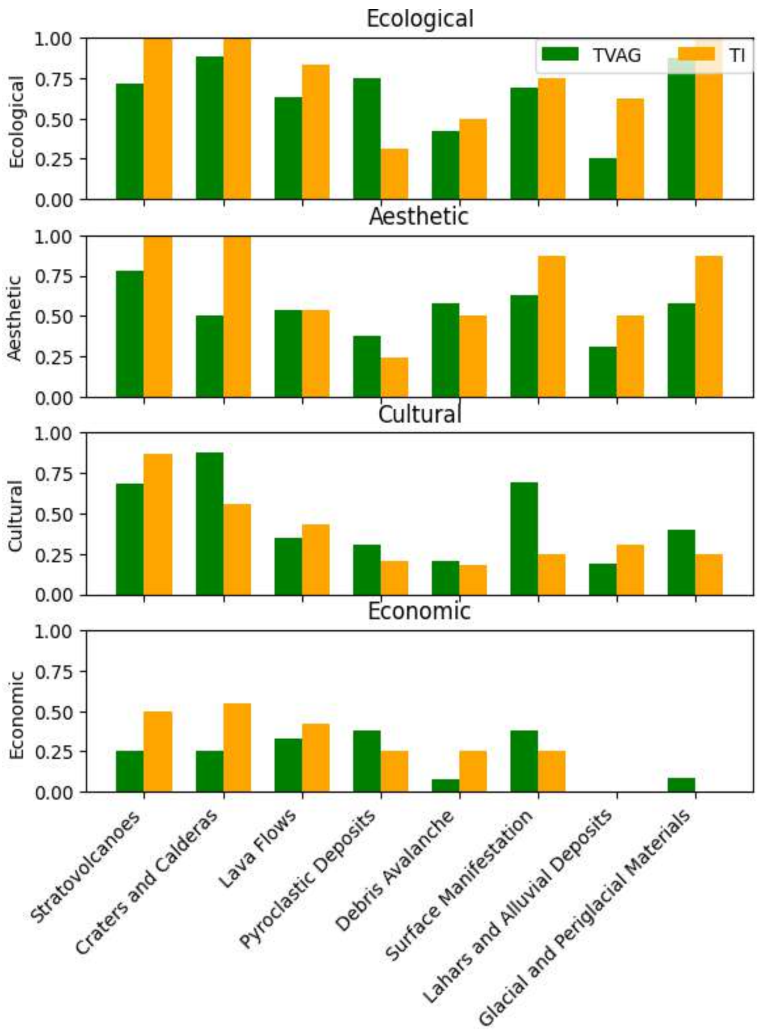


Figure 28 . Additional values vs subgroups selected.

Although accessibility possibilities were evaluated, it is important to highlight aspects such as the topography of each region and how this can influence access to the geosites. TI, with a lower altitude and less rugged terrain compared to the Ecuadorian Andes, can facilitate access to the geosites. Volcanic formations in an intraplate environment can be more accessible due to their extent and lower inclination. In contrast, the Andean topography is more rugged and presents natural barriers such as steep slopes, deep valleys, and difficult access areas due to altitude and dense vegetation. For example, volcanoes like Tungurahua and Chimborazo can reach up to 6,263 meters above sea level (GVT, 2023), while volcanoes in TI like Teide-Pico Viejo reach up to 3,718 meters above sea level (Perez-Umaña et al.,2019).

Regarding cultural values, TI presents higher values in stratovolcanoes (0.87 vs. 0.68 in TVAG). However, TVAG stands out in craters (0.88 vs. 0.56 in TI), lava flows (0.62 vs. 0.43 in TI), and surface manifestations (0.69 vs. 0.25 in TI), which could reflect a greater religious and historical importance in these geosites and a strong cultural and symbolic connection with local communities, such as the

Salasakas and Puruhaes Indigenous communities. For example, TVG06 represents a significant historical area in Ecuador due to the disasters caused by Tungurahua volcano during its eruptive periods, making this region an example of resilience for communities living near volcanoes (GVT, 2023). Likewise, surface manifestations like the geosite TVG14 have a historical association with pre-colonial Indigenous cultures, such as the Quisuuakus (GVT, 2023), making it an attractive site not only for its hydrothermally but also for its archaeological remains.

Economically, both regions show low values overall. However, TI has greater economic potential in craters and calderas (0.50 vs. 0.25 in TVAG), probably due to indirect incomes such as tourism and efficient management of these sites (Dóniz-Páez & Ramírez-Becerra, 2020). For its part, TVAG shows a significantly higher economic value in lava flows (1 vs. 0.42 in TI), highlighting the impact of ecotourism and adventure activities that may be influenced by the fact that along TVG06, it is an indirect source of economic income like tourism (GVT, 2023). Overall, both present low economic values in lahars and alluvial deposits (0 for both), as well in Debris avalanches suggesting lower commercial exploitation of these formations.

4.2 Correlation between scientific and additional values

Following the approach proposed by Marrero-Rodríguez & Dóniz-Páez (2022), a scatter plot was generated showing an upward trend line (Figure 29). The Pearson correlation coefficient obtained is r=0.77, indicating a moderate-high positive correlation. This finding underscores the scientific validity of our work and suggests that geosites with high scientific values also tend to have high additional values, and vice versa.

There is a positive correlation, a notable dispersion in the data is observed. Some geosites, especially in TVAG, show considerable variability, with some points significantly above or below the trend line. Most of these are related to volcanic edifices (TVG01 and TVG02) and eruptive products (TVG06). Overall, this dispersion suggests that, although there is a general trend, other criteria of additional and scientific values might be influencing this trend. On average, TI's geosites cluster closer to the upper right corner of the graph, reinforcing the idea that there is a strong correlation in terms of scientific and additional values.

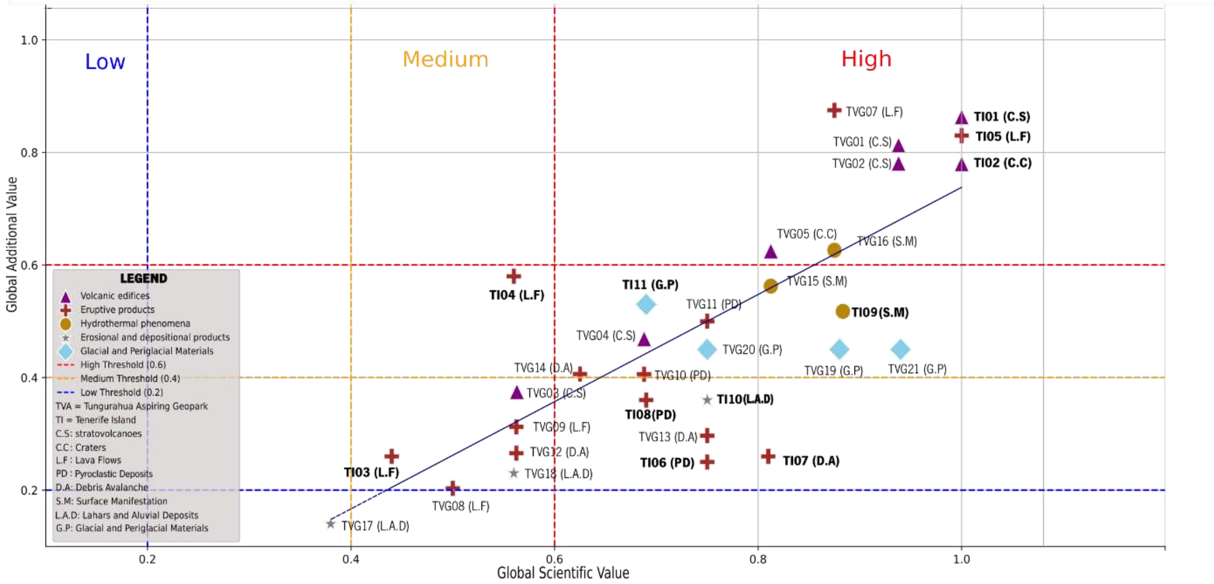


Figure 29. Correlation between scientific and additional values of TVAG and TI.

Although the subgroup of erosional and depositional products, located in the lower-left of the corner, Marrero-Rodríguez & Dóniz-Páez (2022) suggest that, while some geosites may be classified as a low value in scientific or additional terms, and it does not mean they are less important in a broader and local context.

4.3 Proposed classification for the management and conservation of geosites

When correlating the scientific and additional values (Figure 30), we can group the geosites into three categories: low, medium, and high, as done by Marrero-Rodríguez & Dóniz-Páez (2022) and Bouzekraoui et al. (2018). Following these guidelines and in order to manage the geosites in both areas, thresholds were used to classify geosites into these three groups. This classification helps identify which geosites have the greatest interest, an essential information for the management and conservation of these sites. This evaluation is primarily focused on intrinsic values, implying that geosites with higher scores are prioritized for protection and promotion in the context of geotourism. Likewise, those with lower scores are aligned with the objectives of promoting geotourism and developing conservation and sustainable use guidelines for geosites (Marrero-Rodríguez & Dóniz-Páez, 2022)

The grouping is defined as follows:

1. High: Geosites with high scientific and additional values belong to stratovolcanoes, which represent 74% (Figure 32) of the total geosites selected, with TVG01 in TVAG and TI01 in TI being the most representative. Regarding the priority of implementing management

measures, it is important to conduct a Degradation Risk (DR) assessment to establish these priorities and ensure these geosites are conserved and promoted. Knowing the DR of the geosites is essential to support these levels, so in the future, it is important to define the DR for conservation priority

2. Medium: Geosites with moderate scientific and additional values, between 0.40 and 0.60. They are important but do not reach the relevance of high relevance geosite, and represent 23% where TVG03 in TVAG and TI04 in TI are the most representative.
3. Low: Geosites with lower scientific and additional values, between 0.0 and 0.40. They represent around of 3% of the total, where TVG16 in TVAG, is the most representative regarding to lowest values of the whole group.

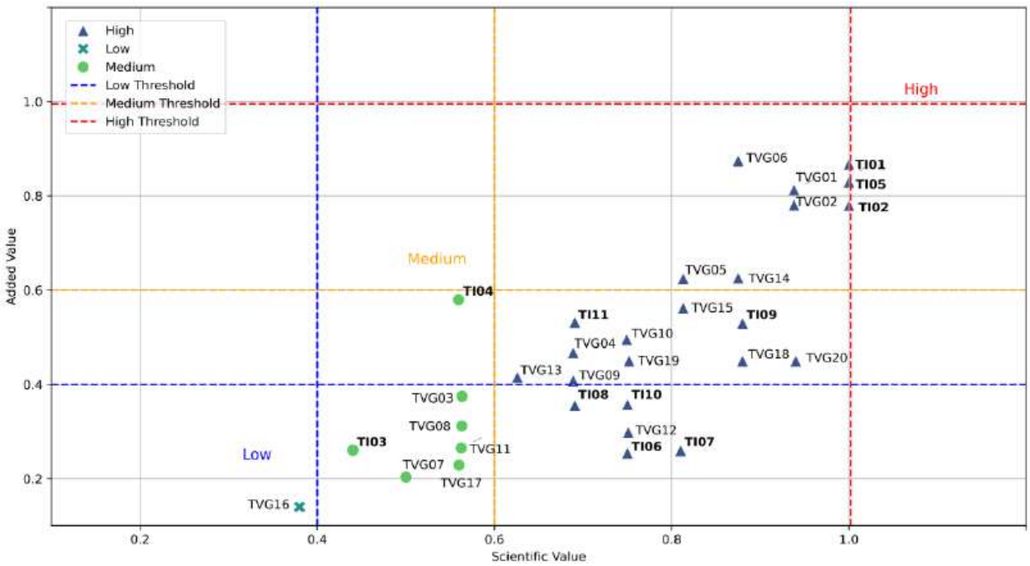


Figure 30. Categories: low, medium, and high, based on their scientific and additional values

It is important to recognize that, although this grouping guides us in prioritizing geosites for conservation and promotion in high, medium, and low relevance categories, it did not evaluate criteria such as degradation risk (DR). According to Brilha (2016), DR is an essential complement for the assessment and for defining a solid strategy when setting management priorities, thus considering sites with both low and high DR can help establish an appropriate management plan.

Indicators such as accessibility, fragility, and vulnerability have not been explored in this master dissertation in comparison with other comparative studies in volcanic areas, such as Pérez-Umaña et al. (2019) . These criteria could be important to explore, especially considering TVAG's highly active tectonic context, which by its own environment makes it fragile. Other relevant indicators, such as proximity to areas or activities with the potential to cause degradation, legal protection, and population density (Brilha, 2016), are also not considered, criteria that could be important to explore due to the fact that TI has been uncontrolled growth of tourism flux, becoming too serious concerns in recent years (Dallavalle et al., 2021).

5. CONCLUSION

The primary objective of this master's dissertation was to propose guidelines for assessing the geotourism potential of geosites in volcanic areas, regardless of their geotectonic and social contexts. This study included geosites from two different geotectonic areas — a subduction zone in Ecuador and an intraplate zone in Tenerife, Canary Archipelago, Spain — that are directly related to volcanic processes, as well as geosites related to other types of processes. Overall, both regions offer unique opportunities for volcanic tourism, independently of their geological context.

The identification, selection, characterization, evaluation, and comparison of volcanic geosites in both areas have revealed significant findings. Tenerife Island (TI) stands out for its geological stability, preservation of stratovolcanoes and calderas, and high accessibility due to its lower altitude and less rugged terrain. In contrast, the Tungurahua Volcano Aspiring Geopark (TVAG) excels in its dynamic and powerful recent volcanic activity, geological diversity in pyroclastic deposits and lava flows, and a strong cultural and economic connection with local communities. TI, with high levels of integrity, representativeness, and aesthetic value due to its limited recent volcanic activity and favorable atmospheric conditions, hosts Teide-Pico Viejo, the third-highest volcanic structure in the world and a site of global significance. Its geological stability has allowed Tenerife to develop a well-established tourist infrastructure, positioning Tenerife as an optimal location to promote volcano tourism and alleviate over-tourism in other parts of the island, thereby preserving its natural beauty.

On the other hand, TVAG, with its high volcanic activity and dynamic geosites interacting with glacial ecosystems, the Amazon rainforest, and mountain grasslands, offers a unique opportunity to explore the interaction between volcanic and tectonic activity, diverse ecosystems, and culture. Despite its rugged accessibility, TVAG provides an ideal setting for volcano tourism in an active subduction context, where visitors can appreciate geological elements, understand volcanic risks, and witness the resilience of local communities living with volcanic activity, fostering a sense of connection and support. Promoting volcano tourism is an optimal strategy to encourage educational and recreational experiences centered on the conservation of unique volcanic landscapes. It offers a deep understanding of the visited sites, where the central elements are the Earth's dynamics, volcanoes, and their associated geological processes. Therefore, promoting this type pf tourism with a greater understanding of geological volcanic processes benefits both study areas.

It is essential to recognize the value of both areas, as they not only offer aesthetic appeal to the general public but also attract those interested in understanding geological processes and volcanism. In this context, scientific tourism, focused on research, advanced education, and participation in scientific projects, plays a crucial role in promoting safety in volcanic regions. These activities, centered on studying and monitoring volcanic activity and collecting data, are essential for managing and mitigating volcanic risks, ensuring the safety of both the scientific community and visitors. Overall, in regions of high scientific relevance like those mentioned, scientific tourism facilitates a deep understanding of the volcanic and tectonic environment, significantly benefiting both scientists and geology enthusiasts.

Results from the assessment conducted have generated a valuable set of geosites that can be included in the inventory of both study areas. This outcome provides a foundation for future conservation initiatives and the promotion of volcanic tourism in both regions, attracting tourists interested in volcanic and educational experiences, and supporting economic and sustainable development.

Regarding the management and conservation of geosites, they were visually grouped into three categories, facilitating the identification of patterns and management priorities (high, medium, low). However, to support the proposed categorization, it is suggested to incorporate additional criteria, such as degradation risk (DR), for a more comprehensive evaluation and robust management strategy. Future research should integrate these criteria to enhance the prioritization and management of geosites, ensuring effective and sustainable conservation.

Overall, the study's limitations include the sample size and variability in geosite characteristics due to their genesis. Future research should expand the sample size. Additionally, quantitative evaluations were not conducted for certain criteria, such as the assessment of use and management values considered by Pérez-Umaña et al. (2020). Overall, assessments will vary depending on the methodology implemented. Methodologies like those of Reynard et al. (2016) generally base the selection of geosites on their scientific values, which depend on different criteria, weights, and perspectives.

Finally, this document supports the objectives of the TVAG consortium in education and science by collaborating on research, theses, internships, and practicums aligned with the research lines applicable to the aspiring geopark territory. The results generated, including the inventory of 31 geosites and their classification and evaluation (20 in TVAG, and 11 in TI), are of significant importance and can be utilized in subsequent studies. These findings provide guidelines for both TVAG and TI regarding their use and management, thereby contributing to the advancement of geotourism in volcanic areas.

Leveraging the extensive 20-year experience of research groups such as GeoTurVol from the University of La Laguna, the Canary Islands Volcanological Institute (INVOLCAN), and the Geological and Mining Institute of Spain (IGME), as well as comprehensive research on the historical volcanism of the Canary Islands, valuable knowledge and lessons have been obtained. These experiences are enriching for the future of the Tungurahua Geopark, being especially relevant for addressing the challenges of conserving and promoting geological heritage in Ecuador.

Appendix

Appendix 1. Qualitative assessment model used for the 31 geosites both in TVAG and TI

Appendix 2. Python Scripts for Data Visualization

A.1 Code for Visualizing a Heatmap of Scientific Values

A.2 Code for Creating Comparative Bar Charts

A.3 Code for Creating a Scatter Plot

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Appendix 1. Qualitative assessment form model used for the 31 geosites both in TVAG and TI

LIGT Nº	NAME OF THE GEOTOURISTIC SITE			
LOCATION	Municipality): Baños, Pelileo, Penipe			
	Coordinates (*) :	X: 784055m E	Y: 9837393m N	Altitud:
DESCRIPCIÓN	The Tungurahua volcano, known as "Garganta de Fuego" in the Kichwa language, is located in the Chambo and Pastaza rivers' hydrographic basins. It falls within the territories of the Baños, Penipe, and Pelileo cantons and stands at an elevation of 5,023 meters above sea level. The volcano's eruptive history spans around 781,000 years, and it is the primary symbol of the Tungurahua Aspiring Geopark. The Sangay National Park, listed as a UNESCO World Natural Heritage site, includes Tungurahua as one of its volcanoes. The Cordillera Real to the east and the Peltetec Fault to the west delineate the structural boundaries of the Alao and Loja litho-tectonic terrains. The Quaternary tectonic features of the La Candelaria Fault lie to the south, and the Patate Fault is located to the north. In addition it is related to Th Baños corridor is situated in close geographical proximity to Tungurahua, stretching across these areas. The explosive activity exhibited transitional phases, ranging from Strombolian, violent Strombolian, Vulcanian, sub-Plinian, phreatomagmatic, ash venting, and low-level pyroclastic flow activity. The composition of the rocks varies between dacitic, andesitic, and andesitic-basaltic. It is composed of three volcanic edifices, out of which two were partially destroyed by large sectoral collapses about 30,000 and 3,000 years ago, respectively. The middle cone is represented by the oldest edifice, Tungurahua I, which dates back from the Middle Pleistocene to the Late Pleistocene. Tungurahua II, from Late Pleistocene to Late Holocene, is characterized by a series of lava flows on the upper southern flank. The youngest edifice, Tungurahua III, is an almost symmetrical cone occupying the western flank and filling the avalanche amphitheater and collapse sectors. It has been marked by nearly continuous eruptive activity, generating lava flows, pyroclastic flows, and debris flows. This edifice's age spans from 2300 to 1400 years ago, with the second period beginning approximately 1200 years ago and continuing to the present day. Additionally, this volcano has experienced approximately seven eruptions in the first millennium AD. One of the significant eruptions occurred either at the end of the 7th century or the beginning of the 8th century. Another major eruption, possibly the strongest during the 8th century, also took place. The last eruption that occurred during the prehistoric period happened during the 14th century AD. Apart from the current active phase (1999-2008), historical records show that four eruptive periods took place after the Spanish conquest, namely 1640, 1773, 1886, and 1916-1918 AD. This stratovolcano presents characteristics such as diamond-shaped structures and conical structures, with its flanks sloping at an angle that varies approximately between 30° and 35°, featuring an internal semi-elliptical crater at its summit. Additionally, the existing landforms are related to constructions of stratovolcanoes, alluvial environments, glacial landscapes, steep reliefs on metamorphic rocks, upper slopes, and reliefs of inter-Andean basins in the northern of the Sierra region with pyroclastic deposits. Overall, this geosite allows learning about volcanic processes, types of eruptions, gas or ash emissions, as well as phenomena such as pyroclastic flows, lahars, fumaroles, and hydrothermal activity. Similarly, it is possible to highlight that, based on the eruptions recorded between 1999 and 2016, it is possible to establish a relationship between risk management and the behavior of eruptive events, meaning it enables knowledge about preparation, recovery, and reconstruction after such events.			
Description of the access itinerary	Located in the hydrographic basins of the Chambo and Pastaza rivers, it is part of the cantons of Baños, Penipe, and Pelileo. The main access to the summit begins in the hamlet of Pondoa, Baños canton; other access points to the north start in Penipe.			
Geotouristic interest	Sangay National Park, Ecuador Historical eruptions, conical volcanic edifice, Myths and legends.			

(*) From the geometric center of the geotouristic site

Geoheritage Assesment			
SCIENTIFIC VALUE (VS)			
Criteria	**Qualitative Assesment**	**State**	**Value**
Integrity (I)	The natural ecosystems are mostly intact, and conservation efforts are ongoing with controlled human impacts and some restoration activities. Resource management is adequate.	Destroyed	0.
		Practically destroyed	0.25
		Partially destroyed	0.5
		lightly damaged	0.5
		Intact	1.
Representativeness (R)	It holds great importance in Ecuador because of its history of eruptions and its inclusion in the Tungurahua Aspiring Geopark and Sangay National Park. This history provides valuable insights into volcanic processes and hazards, which are crucial for conservation and tourism. The volcano's location near the Baños corridor highlights its regional significance, while recent eruptions have shed light on its importance for risk management and disaster preparedness. Therefore, understanding and mitigating the impact of volcanic events on local communities becomes easier.	Null	0.
		weak	0.25
		Moderate	0.5
		High	0.75
		Very high	1.
Rareness (Rz)	Its rarity characterizes it due to several factors. Firstly, it resides amidst agricultural communities that have coexisted with it for generations, showcasing a unique human-nature interaction. Secondly, it is situated within the Baños ecological corridor and forms part of the Sangay Natural Reserve, a UNESCO World Natural Heritage site, underscoring its importance for biodiversity conservation. Thirdly, deeply rooted in Andean culture, Tungurahua is known as "Mama Tungurahua" and holds significant cultural and historical significance, intertwined with local beliefs, myths, and survival stories. Finally, Tungurahua has witnessed rare geological events, such as the memorable "Los Pajaros" pyroclastic flow, which marked a significant moment in Ecuador's volcanic history. These factors collectively contribute to Tungurahua's rarity, making it a focal point of ecological, cultural, historical, and scientific interest.	More than 7	0.
		Between 5 and 7	0.25
		Between 3 and 4	0.5
		Between 1 and 2	0.75
		Unique	1.
Paleographical interest (Ip)	It holds significant importance for Earth and climate history, particularly in understanding the evolution of volcanic landscapes and their impact on the surrounding environment.	Null	0.
		Weak	0.25
		Moderate	0.5
		High	0.75
		Very high	1.
Puntuation	**Vs = (Integrity + Representativeness + Rareness + Paleographical interest) / 4 =**		
Syntesis of scientific value	In no more than four or five lines, summarize the scientific assessment of the site and indicate its hierarchical level based on Bouzekraoui et al., 2017 scale (low, medium, or high)		

ADITIONAL VALUES (V_{AD})			
ECOLOGICAL VALUES (V_{ECO})			
Criteria	**Qualitative Assesment**	**State**	**Value**

Ecological influence	The volcano's location within the Baños ecological corridor and its inclusion in the Sangay Natural Reserve, which is a UNESCO World Natural Heritage site,.	Not related to biological features	0.
		Presence of interesting flora and fauna	0.25
		One of the best places to observe interesting flora and/or fauna	0.50
		Geomorphological features are important for ecosystems	0.75
		Geomorphological features are crucial for ecosystems	1
Site protection	It is included in Sangay National Park	Unprotected	0.
		Locally protected	0.25
		Regionally protected	0.50
		Nationally protected	0.75
		Internationally protected	1
Puntuación V_{ECO}	**V_{ECO} = (Influencia ecológica + Protección del sitio) / 2 =**		
AESTETIC VALUES (V_{AST})			
Criteria	**Qualitative Assesment**	**State**	**Value**
Viewpoints	It's possible to explore many municipalities within geoparks.	only visible in situ or not easily accessible	0
		not easily accessible, but offers 1 or 2 viewpoints	0.25
		It offers some viewpoints (3-5) due to the presence of visual obstacles	0.50
		It has many viewpoints (> 5)	0.75
		It has many viewpoints and is visible from great distances.	**1**
Vertical contrasts, development, and spatial structuring	It exhibits notable vertical contrasts with diverse habitats developing at different elevations. This spatial structuring contributes to the overall ecological complexity and diversity of the area surrounding the volcano.	monotonous: flat topography and monochrome	0
		It displays some vertical development and up to three colors are recognized	0.25
		rugged and up to 5 colors are recognized	0.50
		It displays contrasting topography and up to 7 colors are recognized	0.75
		It displays contrasting and rugged topography, and up to 7 colors are recognized	**1**
Puntuación V_{EST}	**V_{AST} = (Viewpoints + Vertical contrasts, development, and spatial structuring) / 2 =**		
CULTURAL VALUE (V_{CUL})			
Criteria	**Qualitative Assesment**	**State**	**Value**
Religious and s **Symbolic Importance** (I_R)	Related to Indigenous Andean wisdom.	no religious significance	0
		local religious significance	0.25
		provincial or regional religious significance	0.50
		national religious significance	**0.75**

		international religious significance.	1
Historical significance (I_S)	It is culturally significant due to its historical and geological importance, marked by notable eruptions like "Los Pájaros" which impacted the Tungurahua province's memory.	no historical significance	0
		local historical significance	0.25
		provincial or regional historical significance	0.50
		national historical significance	**0.75**
		international historical significance.	1
Artistic and literary importance (I_A)	Artistic creations e.g., paintings, sculptures and books.	No artistic importance	0
		Local artistic importance	0.25
		Regional artistic importance	0.50
		National artistic importance	**0.75**
		International artistic importance	1
Geohistorical significance (I_{GEO})	Active volcanic activity at the location has played a significant role in shaping the landscape over time, providing valuable insights into volcanic processes, including magma composition, eruption styles, and hazards.	The site is not the origin of any discovery throughout the history of Earth Sciences	0
		The site, due to scientific development or demonstration of a process, is locally known	0.25
		The site, due to scientific development or demonstration of a process, is known regionally and/or provincially	0.50
		The site, due to scientific development or demonstration of a process, is known nationally	0.75
		The site, due to scientific development or demonstration of a process, is known international	**1**
Puntuación V_{CUL}	**$V_{CUL} = (I_R + I_S + I_A + I_{GEO}) / 4 =$**		
ECONOMIC VALUE (V_{ECON})			
Criteria	**Qualitative Assesment**		**State**
Econommic products	It generates no income		0
	It is known but causes indirect benefits (tourism)		**0.25**
	It is a source of income but is threatened by human activity that may deplete it.		0.50
	It is managed by a company, causing no impact.		0.75
	It allows for direct management by an autonomous company with no negative impact.		1
Puntuation V_{ECON}			
Aditional Puntuation	**$V_{AD} = (V_{ECO} + V_{AST} + V_{CUL} + V_{ECON}) / 4 =$**		
Additional Assessment Summary	Summarize the added value assessment of the site in no more than four or five lines		

USE AND MANAGEMENT (V_{UM})		
Criteria	**Subcriteria**	**Assesment**
Protection	**Protection**	Located within the Sangay National Park, which shares part of its territory with the Aspiring Geopark of Tungurahua Volcano, there are many routes that offer free entry, as well as some areas with barriers, as certain areas have their own owners. Additionally, this area is closer to the urban areas and main Ecuadorian highways.
	Damages and Threats	Tungurahua Volcano faces a range of damages and threats despite its protected status. Surrounding communities exert pressure on its boundaries, leading to environmental degradation through activities like deforestation and pollution. Moreover, the limited oversight of tourism, while currently modest, presents risks such as habitat disturbance and littering. The volcano's proximity to urban centers like Baños further complicates matters, as human encroachment threatens natural habitats. Additionally, areas outside the park, often privately owned and utilized for tourism, contribute to habitat fragmentation. Perhaps most significantly, ongoing volcanic activity demands constant monitoring to safeguard nearby populations and infrastructure currently controlled by IGEPN. Addressing these challenges demands a multifaceted approach, including enhanced community engagement, stricter tourism management, and robust monitoring systems to ensure the preservation of this vital ecosystem for both present and future generations.
Promotion	**Visit Condition**	Public transportation offers easy access to the main viewpoints in each municipality. However, if visitors want to climb the volcano, the nearest routes are further away. The hike is considered challenging, with some well-maintained trails, but weather conditions and the volcano's topography can cause damage and make navigation difficult. Additionally, several significant risks are identified, such as the possibility of rockfalls, slippery terrain, or areas that are hard to access, which can pose a significant threat to visitor safety. Despite these challenges, numerous positive aspects of the site's environment are documented, making it particularly attractive, including its stunning landscape and tranquil atmosphere.
	Education	Regarding interpretive facilities, existing facilities are not documented. However, there is exceptional potential for educational interpretation, with outstanding suitability for a wide range of visitors, from academics to non-specialists. Geomorphic concepts are presented exceptionally clearly and comprehensibly.

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Appendix 2. Python Scripts for Data Visualization

A.1 Code for Visualizing a Heatmap of Scientific and Additional Values

A.2 Code for Creating Comparative Bar Charts

A.3 Code for Creating a Scatter Plot

A.1

```python
import pandas as pd
import seaborn as sns
import matplotlib.pyplot as plt

# Geositios
data = {
    'Code': ['TVG01', 'TVG02', 'TVG03', 'TVG04', 'TVG05', 'TVG06', 'TVG07', 'TVG08', 'TVG09', 'TVG10', 'TVG11', 'TVG12', 'TVG13', 'TVG14', 'TVG15', 'TVG16', 'TVG17', 'TVG18', 'TVG19', 'TVG2
    'Name': ['Tungurahua', 'Chimborazo', 'Huilsla-Mulmul', 'Igualata', 'El Altar', 'Flujo de Lava Baños',
             'Autobreccia de Bilbao', "Lavas Deformadas del Huilsla-Mulmul", 'Ignimbrita Los Pájaros',
             'Cascadas Mayorasgo', 'Hummocky de Guanandó (30ka)', 'Hummocky de Cotaló (3ka)', 'El Templete', 'Depósito de Travertino Las Caras',
             'Aguas Termales Puela', "Lahar de San Pedro", 'Depósito Alluvial de San Miguel ', 'Valle Glacial de Abraspungo ',
             'Bloques Erraticos del Chimborazo', 'Minas de Hielo  Chimborazo'],
    'Integrity': [0.75, 0.75, 0.5, 0.5, 0.75, 0.75, 0.5, 0.75, 0.5, 1, 0.75, 0.75, 0.5, 0.5, 1, 0.25, 0.5, 1, 0.75, 0.75],
    'Representativeness': [1, 1, 0.25, 0.5, 0.75, 1, 0.25, 0.25, 0.5, 0.5, 0.5, 0.75, 0.5, 1, 1, 0.25, 0.5, 0.75, 0.75, 1],
    'Rareness': [1, 1, 0.75, 1, 1, 1, 0.75, 0.5, 0.75, 1, 0.25, 0.75, 0.75, 1, 0.75, 0.25, 0.75, 0.75, 0.5, 1],
    'Paleographic Interest': [1, 1, 0.75, 0.75, 0.75, 0.75, 0.5, 0.75, 1, 0.5, 0.75, 0.75, 0.75, 1, 0.5, 0.75, 0.5, 1, 1, 1],
    'Score': [0.94, 0.94, 0.56, 0.69, 0.81, 0.94, 0.5, 0.56, 0.69, 0.75, 0.56, 0.75, 0.63, 0.81, 0.88, 0.38, 0.56, 0.88, 0.75, 0.94]
}

# Crear un DataFrame
df = pd.DataFrame(data)

# Actualizar los valores de Paleographic Interest y otros valores solicitados
df.loc[df['Name'] == 'Flujo de Lava Baños', ['Integrity', 'Representativeness', 'Rareness', 'Paleographic Interest']] = [0.75, 1.00, 1.00, 0.75]

# Calcular y añadir la fila 'Average' al DataFrame
average_row = df.mean(numeric_only=True)
average_row['Code'] = 'Average'
average_row['Name'] = 'Average'
df = pd.concat([df, pd.DataFrame([average_row])], ignore_index=True)

# Eliminar cualquier fila adicional de 'Average'
df = df.drop_duplicates(subset=['Code', 'Name'], keep='last')

# Actualizar la columna de Score
df['Score'] = df[['Integrity', 'Representativeness', 'Rareness', 'Paleographic Interest']].mean(axis=1)

# Concatenar "Code" y "Name" para un nuevo índice
df['Code_Name'] = df['Code'] + ' - ' + df['Name']
df.set_index('Code_Name', inplace=True)

# Definir el tamaño de la letra
font_size = 12

# Crear el heatmap con celdas más pequeñas y ajustar el tamaño de las celdas
plt.figure(figsize=(14, 10))
heatmap = sns.heatmap(df.drop(columns=['Code', 'Name']), annot=True, cmap='coolwarm', cbar=True, linewidths=0.5, linecolor='black',
                      xticklabels=['Integrity', 'Representativeness', 'Rareness', 'Paleographic Interest', 'Score'],
                      annot_kws={"size": font_size}, vmin=0, vmax=1)

# Ajustar la leyenda personalizada
colorbar = heatmap.collections[0].colorbar
colorbar.set_ticks([0, 0.2, 0.4, 0.6, 0.8, 1.0])
colorbar.set_ticklabels(['0 - Low', '0.2', '0.4 - Medium', '0.6 - High', '0.8', '1.0'])

# Ajustar el gráfico
plt.title('TVAG Scientific values', fontsize=font_size + 6)
plt.xticks(rotation=0, ha='center', fontsize=font_size)
plt.yticks(rotation=0, fontsize=font_size)
plt.tight_layout()


# Mostrar la figura
plt.show()
```

A.2

```python
import pandas as pd
import matplotlib.pyplot as plt

# Geositios
data = {
    'Region': [
        'TVAG', 'TI', 'TVAG', 'TI', 'TVAG', 'TI', 'TVAG', 'TI',
        'TVAG', 'TI', 'TVAG', 'TI', 'TVAG', 'TI', 'TVAG', 'TI'
    ],
    'Type': [
        'Stratovolcanoes', 'Stratovolcanoes', 'Craters and Calderas', 'Craters and Calderas', 'Lava Flows', 'Lava Flows',
        'Pyroclastic Deposits', 'Pyroclastic Deposits', 'Debris Avalanche', 'Debris Avalanche', 'Surface Manifestation', 'Surface Manifestation
        'Lahars and Alluvial Deposits', 'Lahars and Alluvial Deposits', 'Glacial and Periglacial Materials', 'Glacial and Periglacial Materials
    ],
    'Integrity': [0.63, 1, 0.75, 1, 0.67, 0.75, 0.75, 0.75, 0.67, 0.75, 0.75, 0.75, 0.38, 0.75, 0.83, 0.75],
    'Representativeness': [0.69, 1, 0.75, 1, 0.50, 1, 0.50, 1, 0.58, 0.75, 1, 1, 0.38, 0.75, 0.83, 0.5],
    'Rareness': [0.94, 1, 1, 1, 0.75, 0.58, 0.88, 0.50, 0.58, 0.50, 0.88, 1, 0.50, 0.75, 0.75, 0.5],
    'Paleographic Interest': [0.88, 1, 0.75, 1, 0.67, 0.33, 0.75, 0.88, 0.75, 0.75, 0.75, 0.75, 0.63, 0.75, 1, 1],
    'Ecological': [0.71875, 1, 0.88, 1, 0.63, 0.83, 0.75, 0.31, 0.42, 0.5, 0.69, 0.75, 0.25, 0.62, 0.875, 1],
    'Aesthetic': [0.78125, 1, 0.5, 1, 0.54, 0.38, 0.245, 0.58, 0.5, 0.63, 0.87, 0.31, 0.5, 0.58, 0.87],
    'Cultural': [0.6875, 0.87, 0.88, 0.56, 0.35, 0.43, 0.31, 0.21, 0.21, 0.18, 0.69, 0.25, 0.19, 0.31, 0.4, 0.25],
    'Economic': [0.25, 0.5, 0.25, 0.55, 0.33, 0.42, 0.38, 0.25, 0.08, 0.25, 0.38, 0.25, 0, 0, 0.083, 0]
}

# Crear DataFrame
df = pd.DataFrame(data)

# Definir los criterios científicos y adicionales
scientific_criteria = ['Integrity', 'Representativeness', 'Rareness', 'Paleographic Interest']
additional_criteria = ['Ecological', 'Aesthetic', 'Cultural', 'Economic']

# Colores específicos para cada región
colors = {'TVAG': 'green', 'TI': 'orange'}

# Crear gráficos de barras para criterios científicos
fig, axes = plt.subplots(nrows=len(scientific_criteria), ncols=1, figsize=(14, 28))


types = df['Type'].unique()
ind = range(len(types))  # the label locations

for i, criterion in enumerate(scientific_criteria):
    ax = axes[i]
    width = 0.35  # width of the bars

    tungurahua_values = df[df['Region'] == 'TVAG'][criterion].values
    tenerife_values = df[df['Region'] == 'TI'][criterion].values
```

```
    tungurahua_values = df[df['Region'] == 'TVAG'][criterion].values
    tenerife_values = df[df['Region'] == 'TI'][criterion].values

    p1 = ax.bar([x - width/2 for x in ind], tungurahua_values, width, label='TVAG', color=colors['TVAG'])
    p2 = ax.bar([x + width/2 for x in ind], tenerife_values, width, label='TI', color=colors['TI'])

    ax.set_title(criterion)
    if i == len(scientific_criteria) - 1:  # Only set x-ticks for the last plot
        ax.set_xticks(ind)
        ax.set_xticklabels(types, rotation=45, ha="right", fontsize=10)
        ax.set_xlabel('Type')
    else:
        ax.set_xticks(ind)
        ax.set_xticklabels([])
    ax.set_ylabel(criterion)
    ax.set_ylim(0, 1)  # Set Y-axis scale from 0 to 1

# Añadir la leyenda
fig.legend(['TVAG', 'TI'], loc='upper center', ncol=2, bbox_to_anchor=(0.5, 0.98))

plt.tight_layout(rect=[0, 0.03, 1, 0.95])
plt.show()

# Crear gráficos de barras para criterios adicionales
fig, axes = plt.subplots(nrows=len(additional_criteria), ncols=1, figsize=(14, 28))
fig.suptitle('', fontsize=16)

for i, criterion in enumerate(additional_criteria):
    ax = axes[i]
    width = 0.35  # width of the bars

    tungurahua_values = df[df['Region'] == 'TVAG'][criterion].values
    tenerife_values = df[df['Region'] == 'TI'][criterion].values

    p1 = ax.bar([x - width/2 for x in ind], tungurahua_values, width, label='TVAG', color=colors['TVAG'])
    p2 = ax.bar([x + width/2 for x in ind], tenerife_values, width, label='TI', color=colors['TI'])

    ax.set_title(criterion)
    if i == len(additional_criteria) - 1:  # Only set x-ticks for the last plot
        ax.set_xticks(ind)
        ax.set_xticklabels(types, rotation=45, ha="right", fontsize=10)
        ax.set_xlabel('Type')
    else:
        ax.set_xticks(ind)
        ax.set_xticklabels([])
    ax.set_ylabel(criterion)

# Añadir la leyenda
fig.legend(['TVAG', 'TI'], loc='upper center', ncol=2, bbox_to_anchor=(0.5, 0.98))

plt.tight_layout(rect=[0, 0.03, 1, 0.95])
plt.show()
```

A.3

```
import pandas as pd
import matplotlib.pyplot as plt
import seaborn as sns
import numpy as np
from adjustText import adjust_text
from scipy.stats import linregress

# Crear un DataFrame a partir de los datos proporcionados, incluyendo grupos y subgrupos
data = {
    "Code": [
        "TVG01", "TVG02", "TVG03", "TVG04", "TI01", "TVG05", "TI02", "TVG06", "TVG07",
        "TVG08", "TVG09", "TI03", "TI04", "TI05", "TVG10", "TI06", "TVG11", "TI07",
        "TVG12", "TVG13", "TVG14", "TI08", "TVG15", "TVG16", "TI09", "TVG17", "TVG18",
        "TI10", "TVG19", "TVG20", "TVG21", "TI11"
    ],
    "Name": [
        "Tungurahua", "Chimborazo", "Huisla-Mulmul", "Igualata", "Teide-Pico viejo",
        "El Altar", "Caldera de las Cañadas", "Flujo de Lava Baños", "Pailon del Diablo",
        "Auto-brecha de Bilbao", "Deformación lávica del Huisla-Mulmul", "Margarita de Piedra",
        "Malpais de Guilmar", "Barranco del Infierno", "Ignimbrita de Juive Grande",
        "Playa deTajao", "Cascafa Mayorasgo", "Tarta del Teide", "Hummocky de Guanandó (30ka)",
        "Hummocky de Cotaló (3ka)", "El templete", "Playa de Abadaes", "Las Caras Travertine Deposits",
        "Aguas Termales de Puela", "Azulejos de Ucanca", "Lahar de San Pedro", "Deposito Aluvial San Miguel",
        "Rambla de los caballos", "Valle Glacial Abraspungo", "Chimborazo's Erratic field",
        "Minas de Hielo del Chimborazo", "La forteza"
    ],
    "Global Scientific Value": [
        0.938, 0.938, 0.563, 0.688, 1.000, 0.8125, 1.000, 0.6875, 0.875, 0.5, 0.5625, 0.44,
        0.56, 1.000, 0.688, 0.75, 0.75, 0.81, 0.5625, 0.75, 0.625, 0.69, 0.8125, 0.875,
        np.nan, 0.38, 0.56, 0.75, 0.88, 0.75, 0.94, 0.69
    ],
    "Global Additional Value": [
        0.813, 0.781, 0.375, 0.469, 0.84, 0.625, 0.78, 0.8125, 0.875, 0.203125, 0.3125, 0.26,
        0.58, 0.83, 0.406, 0.25, 0.5, 0.26, 0.265625, 0.296875, 0.40625, 0.36, 0.5625, 0.62625,
        np.nan, 0.14, 0.23, 0.36, 0.45, 0.45, 0.45, 0.53
    ],
    "Group": [
        "Volcanic edifices", "Volcanic edifices", "Volcanic edifices", "Volcanic edifices",
        "Volcanic edifices", "Volcanic edifices", "Volcanic edifices", "Eruptive products",
        "Eruptive products", "Eruptive products", "Eruptive products", "Eruptive products",
        "Eruptive products", "Eruptive products", "Eruptive products", "Eruptive products",
        "Eruptive products", "Eruptive products", "Eruptive products", "Eruptive products",
        "Eruptive products", "Eruptive products", "Hydrothermal phenomena", "Hydrothermal phenomena",
        "Hydrothermal phenomena", "Erosional and depositional products", "Erosional and depositional products",
        "Erosional and depositional products", "Glacial and Periglacial Materials", "Glacial and Periglacial Materials",
        "Glacial and Periglacial Materials", "Glacial and Periglacial Materials"
```

```python
    ],
    "Subgroup": [
        "C.S", "C.S", "C.S", "C.S", "C.S", "C.C", "C.C", "L.F", "L.F", "L.F", "L.F",
        "L.F", "L.F", "L.F", "PDC", "PFD", "PFD", "D.A", "D.A", "D.A", "D.A",
        "S.M", "S.M", "S.M", "L.A.D", "L.A.D", "L.A.D", "G.P", "G.P", "G.P", "G.P"
    ]
}

# Añadir un valor faltante a la lista Subgroup
data["Subgroup"].append("G.P")

# Crear el DataFrame
df = pd.DataFrame(data)

# Eliminar filas con valores NaN y resetear el índice
df = df.dropna().reset_index(drop=True)

# Separar los geositios por área
df_tungurahua = df[df['Code'].str.startswith('TVG')]
df_tenerife = df[df['Code'].str.startswith('TI')]

# Calcular el coeficiente de correlación de Pearson
correlation = df["Global Scientific Value"].corr(df["Global Additional Value"])

# Calcular la línea de regresión
slope, intercept, r_value, p_value, std_err = linregress(df["Global Scientific Value"], df["Global Additional Value"])

# Crear una paleta de colores específica para cada grupo
color_dict = {
    "Volcanic edifices": "purple",
    "Eruptive products": "brown",
    "Hydrothermal phenomena": "darkgoldenrod",  # Cambiado a un color mostaza oscuro
    "Erosional and depositional products": "grey",
    "Glacial and Periglacial Materials": "skyblue"
}

# Crear un diccionario de símbolos basado en los grupos
marker_dict = {
    "Volcanic edifices": "^",
    "Eruptive products": "P",
    "Hydrothermal phenomena": "o",
    "Erosional and depositional products": "*",
    "Glacial and Periglacial Materials": "D"
}


# Gráfico de Dispersión con Etiquetas de Geositios (códigos)
plt.figure(figsize=(16, 12))

# Añadir los puntos de Tungurahua
for group in df_tungurahua['Group'].unique():
    subset = df_tungurahua[df_tungurahua['Group'] == group]
    sns.scatterplot(x="Global Scientific Value", y="Global Additional Value", data=subset,
                    color=color_dict[group], s=200, edgecolor="w", label=group, marker=marker_dict[group])

# Añadir los puntos de Tenerife
for group in df_tenerife['Group'].unique():
    subset = df_tenerife[df_tenerife['Group'] == group]
    sns.scatterplot(x="Global Scientific Value", y="Global Additional Value", data=subset,
                    color=color_dict[group], s=200, edgecolor="w", label=group, marker=marker_dict[group])

# Dibujar las líneas de umbral
plt.axhline(0.6, color='r', linestyle='--', label='High Threshold (0.6)')
plt.axhline(0.4, color='orange', linestyle='--', label='Medium Threshold (0.4)')
plt.axhline(0.2, color='blue', linestyle='--', label='Low Threshold (0.2)')
plt.axvline(0.6, color='r', linestyle='--')
plt.axvline(0.4, color='orange', linestyle='--')
plt.axvline(0.2, color='blue', linestyle='--')

# Extender el eje Y hasta 1.2
plt.ylim(0.1, 1.2)
plt.xlim(0.1, 1.2)
plt.xticks(np.arange(0.2, 1.3, 0.2))
plt.yticks(np.arange(0.2, 1.3, 0.2))

# Etiquetar las secciones de Low, Medium, High
plt.text(0.1, 1.1, 'Low', horizontalalignment='center', verticalalignment='center', fontsize=12, color='blue')
plt.text(0.5, 1.1, 'Medium', horizontalalignment='center', verticalalignment='center', fontsize=12, color='orange')
plt.text(0.9, 1.1, 'High', horizontalalignment='center', verticalalignment='center', fontsize=12, color='red')

# Añadir etiquetas a los puntos con subgrupos, colores específicos y evitando sobrelapamiento
texts = []
for i in range(df.shape[0]):
    if df["Code"][i].startswith('TVG'):
        weight = 'normal'
        color = 'black'
    else:
        weight = 'bold'
        color = 'black'
    texts.append(
```

```python
        plt.text(x=df["Global Scientific Value"][i] + 0.01,
                 y=df["Global Additional Value"][i] + 0.01,
                 s=f'{df["code"][i]} ({df["Subgroup"][i]})',
                 fontdict=dict(weight=weight, color=color, size=12, family='NewsGotT'))
    )

# Ajustar las posiciones de las etiquetas para evitar sobrelapamiento
adjust_text(texts)

# Añadir descripciones de las áreas a la leyenda
plt.scatter([], [], c='black', alpha=0.5, s=200, label='TVA = Tungurahua Aspiring Geopark')
plt.scatter([], [], c='black', alpha=0.5, s=200, label='TI = Tenerife Island')

# Añadir descripciones de los subgrupos a la leyenda
subgroup_legend_labels = {
    "C.S": "Composite and stratovolcanoes",
    "C.C": "Craters and Calderas",
    "L.F": "Lava Flows",
    "PDC": "PDC",
    "PFD": "PFD",
    "D.A": "Debris Avalanche",
    "S.M": "Surface Manifestation",
    "L.A.D": "Lahars and Aluvial Deposits",
    "G.P": "Glacial and Periglacial Materials and landforms"
}

# Añadir descripciones de subgrupos a la leyenda sin colores
for key, value in subgroup_legend_labels.items():
    plt.scatter([], [], c='black', alpha=0.0, s=200, label=f'{key}: {value}')

# Ajustar la leyenda final
handles, labels = plt.gca().get_legend_handles_labels()
by_label = dict(zip(labels, handles))
plt.legend(by_label.values(), by_label.keys(), bbox_to_anchor=(1.05, 1), loc='upper left', fontsize='medium', title='LEGEND')

# Añadir la línea de regresión
x = df["Global Scientific Value"]
y = df["Global Additional Value"]
plt.plot(x, slope * x + intercept, color='darkblue', linestyle='--', linewidth=1, label=f'Fit line (R={r_value:.2f})')

plt.grid(True)

# Guardar el gráfico como SVG
plt.savefig("geosites_scatter_plot.svg", format='svg')

plt.show()
```