# UNIVERSIDAD DE INVESTIGACIÓN DE TECNOLOGÍA EXPERIMENTAL YACHAY

**Escuela de Ciencias de la Tierra, Energía y Ambiente**

# TÍTULO: Proposal for the characterization and classification of the stratigraphic units associated with the proximal volcanic deposits of the Ecuadorian Quaternary Arc

Trabajo de integración curricular presentado como requisito para la obtención del título de Geólogo


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# Dedication

To my beloved mother, whose unwavering support, boundless love, and constant encouragement have been the cornerstone of my journey. Your sacrifices, faith in my abilities, and relentless optimism have been my guiding light, inspiring me to reach for my dreams and persevere through every challenge. This achievement is as much yours as it is mine, for without your nurturing spirit and endless devotion, none of this would have been possible. Thank you for being my rock, my confidante, and now, my greatest angel.

Fausto Vizcaíno

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To all of you, my deepest gratitude.

Fausto Vizcaíno

# Resumen


El arco volcánico ecuatoriano, situado dentro de la Cordillera de los Andes, cuenta con más de 80 centros eruptivos que presentan una gran diversidad geológica. En las últimas décadas, se han realizado estudios estratigráficos y geocronológicos extensos, la cartografía de estos centros eruptivos carece de un método estandarizado para la caracterización y clasificación de las unidades litoestratigráficas. Este trabajo, busca sintetizar la información reciente proponiendo un esquema de clasificación cohesivo y estandarizado para la identificación y organización de estas unidades volcánicas. Los mapas geológicos actuales de los volcanes de Ecuador, como en Cotacachi, Imbabura, Antisana, Pichincha, and Tungurahua utilizan diferentes criterios de clasificación, lo que resulta en una falta de uniformidad. Una revisión del estándar nacional generado por el Instituto de Investigación Geológica y Energética (IIGE) demuestra que este insumo, resulta inadecuado para aplicaciones de depósitos del cuaternario. Este trabajo de integración curricular propone consolidar criterios de estándares de clasificación internacionales de países como EE.UU., Italia y Nicaragua, para crear un esquema cohesivo aplicable a Ecuador. Mediante ejemplos locales, se ilustra la coherencia de la propuesta con las realidades geológicas ecuatorianas, incluyendo definiciones básicas y la sugerencia de actualizar el mapa de volcanes a escala 1:500,000 generado por el *Instituto Geofísico* Instituto Geofísico de la Escuela Politécnica Nacional (IG-EPN).


**Palabras Clave**: El arco volcánico ecuatoriano, centros eruptivos, unidades litoestratigráficas, unidades volcánicas, mapas geológicos, estándares de clasificación, mapa de volcanes.

# Abstract

The Ecuadorian volcanic arc, located within the Andes Mountains, has more than 80 eruptive centers that present a great geological diversity. In the last decades, extensive stratigraphic and geochronological studies have been carried out. Still, the mapping of these eruptive centers lacks a standardized method for the characterization and classification of the lithostratigraphic units. This work aims to synthesize recent information by proposing a cohesive and standardized classification scheme for the identification and organization of these volcanic units. Current geological maps of volcanoes in Ecuador, such as Cotacachi, Imbabura, Antisana, Pichincha, and Tungurahua use different classification criteria, resulting in a lack of uniformity. A review of the national standard generated by the Instituto de Investigación Geológico y Energético (IIGE) shows that this input is inadequate for Quaternary deposit applications. This curriculum integration work proposes to consolidate criteria from international classification standards from countries such as the USA, Italy, and Nicaragua to create a cohesive scheme applicable to Ecuador. Using local examples, it illustrates the coherence of the proposal with Ecuadorian geological realities, including basic definitions and the suggestion to update the 1:500,000 scale map of volcanoes generated by the Instituto Geofísico de la Escuela Politécnica Nacional (IG-EPN).

**Keywords**: Ecuadorian volcanic arc, eruptive centers, lithostratigraphic units, volcanic units, geological maps, classification standards, volcano map.

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# Chapter 1

# Introduction

## 1.1 Background

The Ecuadorian volcanic arc is a huge volcanic arc located in the inner Andes of Ecuador. It consists of 78 volcanoes that shape its landscape. The boundary structure and subdivision of the Ecuadorian volcanic arc are shown in Figure 1.1. These volcanoes have been the focus of stratigraphic and geochronologic studies over time (Santamaria et al., 2024). However, there is still a lack of appropriate criteria to define and distinguish their products for the denomination of lithostratigraphic units when mapping these volcanic centers. For Ecuador, the lack of a deposit classification framework is an obstacle to the production of comprehensive and consistent geologic maps. Inconsistencies between the categorization systems used by different entities make it difficult to evaluate and compare data (Cas & Wright, 1987). Houghton and Gonnermann (2008) proposed that a classification system would serve to resolve such problems by facilitating the labeling and compilation of geological maps based on correct, usable materials. Németh and Kereszturi (2015) took this concept a step further in terms of process and structure representations that enable data integration.

Recently, researchers like to classify a system as in previous works, which could facilitate the comparison and communication papers within communities. However, to be able to set the criteria requirements it is also crucial, as Cas and Wright rightly noted back in 1987, that if we desire connection between' regions then definition of deposits need figure uniformly works per area. It is also important to use the same terminology when describing these deposits (Smith & Németh, 2017). These are the foundations for creating a classification system in Ecuador for all volcanoes, using some of the existing criteria from other frameworks and ideas used around the world (Nicaragua, USA, Italy).

The application of these approaches to the characteristics of the Ecuadorian arc will improve forward geological models and lead to a more unified understanding of local volcanic behavior (Cashman, Stephen, & Sparks, 2013). Ecuador has been the subject of significant research and system-based investigations. A broader assessment of the petrology and geology of the Tungurahua and Cayambe volcanoes, focusing on deposit classification, reveals inconsistencies that complicate comparisons (Hall, Robin, Beate, Mothes, & Monzier, 1999; Samaniego et al., 2005). Note that maps of Ecuador have weaknesses. For example, on some maps, it says Mount Santa Elena (Andrade et al., 2019), and for the Cotopaxi, Antisana volcanoes, the focus added on specify materials as seen in Hall et al. (2017).

The approach of reviewing global frameworks based on established criteria applied in Nicaragua, USA and Italy leads us to use this analysis as a basis for categorizing new proposals and defines by itself how it works correctly with regard to the volcanic conditions specifically found in Ecuador. These mechanisms prioritize the inclusion of stratigraphic, petrologic, and morphologic information in the geologic maps (Harris & Ripepe, 2007; Marzocchi & Woo, 2009). The use of these methods in the specific case we are working on here - the Ecuadorian volcanic arc - will make new geological representations much more reliable, facilitating a better regular understanding of local volcanism (Cashman et al., 2013).

In Ecuador geoscientific research has been conducted widely; the country hosts a dynamic volcanic system in South America. A systematic review of the structure and mineralogy of Tungurahua, working with volcanic rocks shows that there are inconsistent challenges in identifying standards for classifying deposits The geologic maps of Ecuador's volcanoes are quite different, and it is within these differences that some interesting lessons emerge. Some of them pass through Mt. Santa Elena e.g., Andrade et al. (2019) or are driven by the classification of volcanic products, as in the case of Cotopaxi and Antisana volcanoes (Hall et al., 2017). Other approaches include focusing the study on a type of eruption history illustrated by Iliniza volcano Santamaría et al. (2022), or identifying discontinuities in morphological relationships such as those shown at Tungurahua volcano (Hall et al., 1999). One of the major hurdles to understanding regional volcanism is the diversity of categorization methods.

The national standard developed by the *Instituto de Investigación Geológico y Energético* (IIGE) is also unsatisfactory for Quaternary applications. The current standard names volcanic units based on their composition and the outcrop or volcano where they are found, e.g., Andesite-Cotopaxi, Dacite-Chachimbiro. However, this approach does not take into account the specifics of each volcano. Although this is helpful in itself, it takes little account of the details of volcanic geology (Hall et al., 2017).

This study aims to integrate the available data by introducing a systematic categorization methodology that follows established criteria and definitions for the identification, classification, and inventory of volcanic units. The recommended classification unifies a system of those proposed for the world (Nicaragua, USA, and Italy), adopting them with the geological background of Ecuador. The methodology is applied in the present work, comparing it with local cases: volcano, volcanic structure, and eruptive event (cores); also proposing changes to the *Mapa de los Volcanes Cuaternarios del Ecuador 1:500K* (B. Bernard & Andrade, 2011) .

Here, a new methodology is defined to incorporate global categorization criteria along with the geology of this unique volcanic arc in Ecuador. This project aims to improve the overall understanding of volcanic events by implementing a unified classification system for the area. This would improve the traceability and readability of geological maps. The purpose of the proposed framework is to develop a common system for describing and cataloging volcanic units in order to improve the accuracy and performance of geological analysis (Newhall & Hoblitt, 2002).

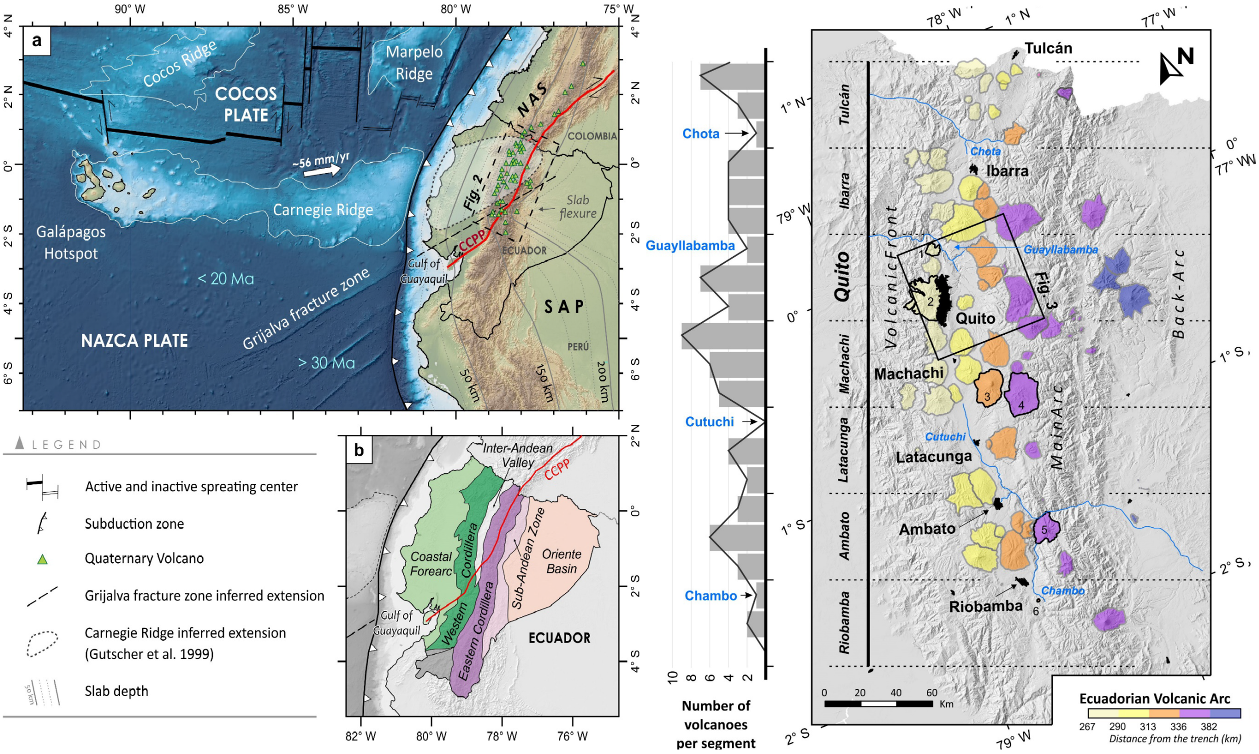


Figure 1.1: Geodynamic setting of the Ecuadorian margin. Segmentation of the Ecuadorian volcanic arc. (Modified from: Santamaria et al. (2024))

## 1.2 Justification

The volcanic arc of Ecuador is one of the geological features that are more conspicuous as they emerge in the Andean mountain range. It is a very complex tectonic setting and is very active in volcanic eruptions (Bablon et al., 2020). This arc forms part of the around-the-Pacific Rim-of-Fire, where subduction (Nazca Plate is pushed under the South American Plate) has produced a series ($\tilde{6}$ km high Axis of the Andes edifice jumped with peaks), chains of volcanoes (Stern, 2011). The arc is well known for its diverse volcanic products, ranging from basaltic to rhyolitic in composition (Tilling, 2009). These differences show magmatic origins and underlying geotectonic processes (Bablon et al., 2020). The area includes a number of volcanic features such as stratovolcanoes, shield volcanoes, or calderas that indicate different phases and locations where magma has accumulated over time (e.g., B. Bernard and Andrade. The geological significance of the Ecuadorian volcanic arc is related to low latitude relative to the equator and the resulting temperature and vegetation patterns (Bluth & Kump, 1994).

Establishing the appropriate stratigraphic framework and classification of volcanic deposits in the Ecuadorian Quaternary Arc is relevant for interpreting geological complexity. The lack of a common methodology has led to the development of numerous geological maps using different classifications, which in turn makes it difficult to compare studies. This gap in the method of study, hinders scientific understanding (Cas & Wright, 1987).

Standardization of categorization techniques is an important improvement that allows geologic results to be compared and communicated more efficiently. Uniform standards for classifying volcanic deposits allow for comparative studies between different volcanic regions and individual papers (Cas & Wright, 1987). Furthermore, the numerous types of volcanic deposits indicate the need for standard terminology to ensure consistent definitions and interpretations (Smith & Németh, 2017).

Research in Ecuador has greatly increased the knowledge of the country's volcanoes. However, it has also revealed variability in the classification of volcanic deposits. These results further emphasize the need for a mutually recognizable classification system that incorporates global standards and regionally complex geological settings (Hall et al., 1999; Samaniego et al., 2005).

This proposal aims to address all of the above issues and create an umbrella classification system based on country-based factors as well as a globally accepted set of definitions. This paper seeks to establish a solid and consistent base, anchored to international standards, for the Ecuadorian vulcanological characteristics.

## 1.3 Problem statement

Here, it is presented an approach to research the effect of using a consistent classification on the homogenization and organization of disintegrated volcanic clasts erupted by proximal Ecuadorian Quaternary volcanoes. Another objective of this study is to evaluate whether such a system improves the uniformity and practical application on geological maps of Ecuador.

This work is specifically focused on the continental surface of Ecuador, in order to provide a complete and homogeneous volcanic classification for all the volcanic units that make up this part of the Andean volcanic arc. It should be noted, however, that the methods and concepts presented here could be applied to any of the Galápagos volcanic islands. A standardized method could be useful for classifying the geologic characteristics and eruptive behavior of volcanic landforms in Galápagos, Ecuador. This study can be extended to mainland Ecuador and the Galápagos Islands by further detailing these criteria to improve our understanding of the national volcanic stratigraphy (Fig. 1.2.

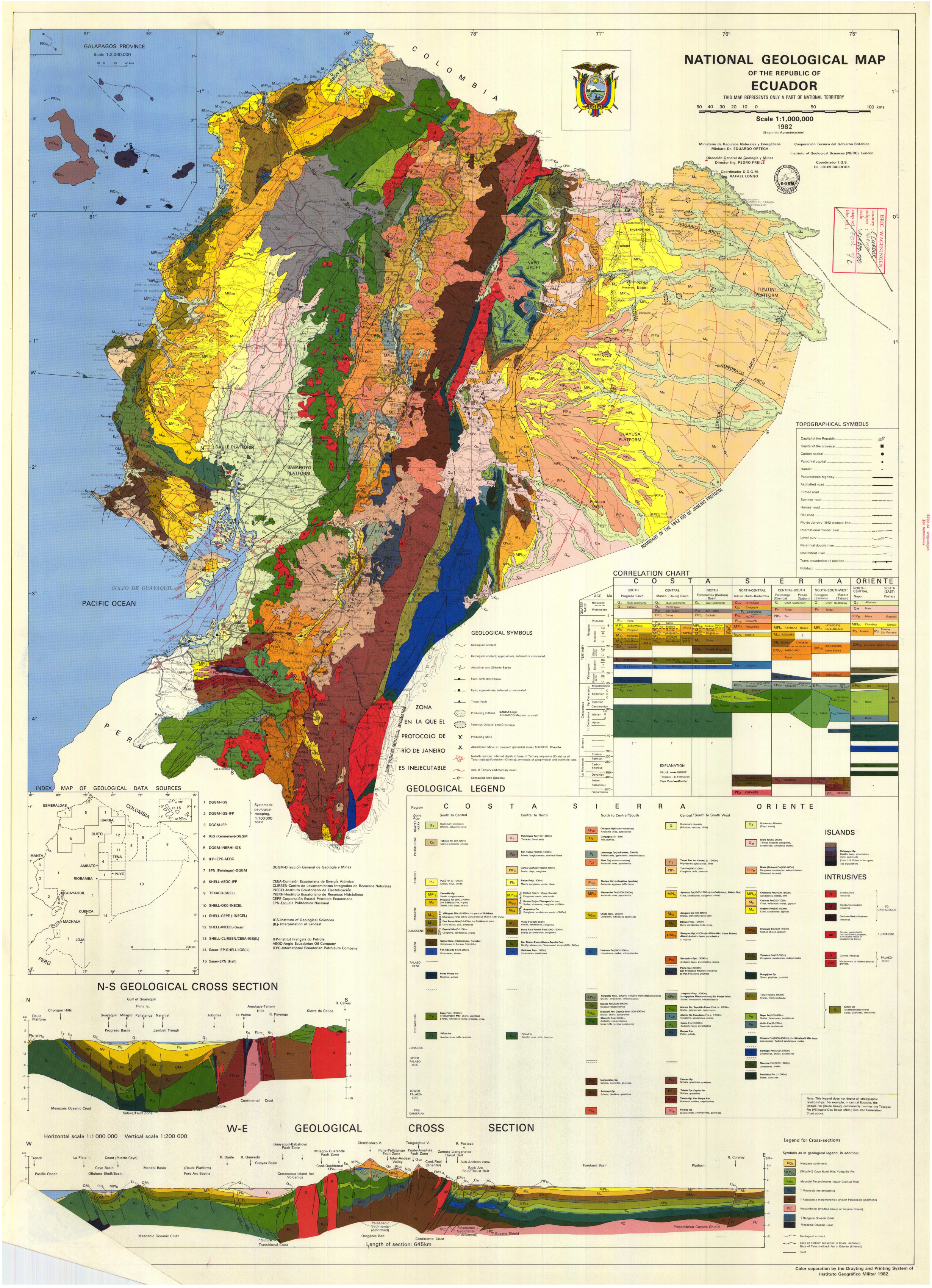


Figure 1.2: National Geological Map of the Republic of Ecuador (including Galápagos Province) (Taken from: Longo and Baldock (1982)

The proposed group covers many important aspects of the Antisana volcano. This is further evidenced by the peculiar context of andesitic volcanism in the northern Andes, its general aspect contrasting with rather dispersed volcanic activity with a late shift towards dacite activity at this particular latitude, as well as an interesting geological record where a considerable part of age fixation-restoration took place for 400 ka. Cuicocha is one of the larger calderas known to have been formed by explosive eruptions over a basement and lava flows from Cotacachi volcano, so geologically it links its eruptive history within the same volcanic complex. It is hoped that the program will then be used to create consistent classifications as a trustworthy basis for understanding volcanism in Ecuador. This will help enable sustainable future research on volcanic hazards and the broader geological context involved.

In addition, a general classification system has the potential to improve the ability to predict volcanic eruptions and thus improve risk prevention. It is also important to know eruptive histories before it is possible for future volcanic activity to occur (Newhall & Hoblitt, 2002). Using a standardized system for categorizing volcanoes across the geo-scientific community allow ensuring a suitable understanding of how past volcanic events were developed and what structures determine risk at different levels.

This systematic approach to geological categorization aims to provide a solid baseline of the Ecuadorian volcanic arc. The commitments of this initiative to scientists, planners or geologists who study in one way or another the impact of volcanism on regional functions can serve as benchmark studies for study and management efforts to volcanic landscape threats.

## 1.4 Objectives of the review

### 1.4.1 General Objective

The primary goal of this work is to develop a reference manual for categorizing units linked to volcanic formations in the Quaternary Arc of Ecuador. This involves examining published works on deposits found in key volcanoes locally and globally. The examination is focused on understanding the methods and approaches used for classifying and describing these deposits. To ensure the manual's accuracy and reliability, it will undergo validation by comparing it with established classification systems.

### 1.4.2 Specific Objectives

· Review as many studies of volcanic deposit classification systems as possible, focusing specifically on international standards.

· Identify and analyze the classification as well as characterization schemes used in several studies of representative volcanoes worldwide. This is focused on those which can then be applied to Ecuador's Quaternary volcanic arc.

· Design a comprehensive classification manual that would include standards for making anywhere up-to-the-minute lithostratigraphic units, with standards derived from lithology, stratigraphy, and any other relevant criterion.

· Apply the classification manual to a number of typical Ecuadorian case studies so as to assess its effectiveness and relevance in describing volcanoes near the source.

· Approach the proposed classification scheme fairly by comparing it with international standards and reviewing the impact it could have on getting Ecuador's geological maps checked and updated.

· Give practical advice as to how this approach would work in practice with regard to Ecuador's volcanic risk management and geological mapping.

# Chapter 2

# Theoretical framework and Methodology

## 2.1 The Ecuadorian Volcanic Arc

The Ecuadorian volcanic arc is home to a tangled web of volcanoes with no fewer than 79 of them arranged in this ride. These volcanic areas have evolved into distinct ”volcanic corridors” (or zones) and ”volcanic clusters,” which reflect the complex brutal reality of this landscape’s geological change. This arc’s location lies in the Western Cordillera, Cordillera Real and Sub-Andean Zone, within an area stretching from Equator to Galapagos Islands. The because of this arc is the result of the subduction process, in which the Nazca Plate is forced under the South American Plate. There are two objects in this region that are quite important: first, what happens to that geologically (since the subduction of the Nazca Plate by the South American Plate has profound effects at this margin), and secondly its impact on densely populated cities such as Quito (which stand immediately next to several active volcanoes). Following the recent activities of volcanoes such as Tungurahua, Pichincha and El Reventador, assessments are needed in order to devise appropriate prevention measures (Hall et al., 2004, 1999; Robin et al., 2010).

### 2.1.1 Volcanic corridors and segmentation

The Ecuadorian volcanic arc has three main arcs of volcanism that run north to southeast and south to southwest. These are the Volcanic Front, the Main Arc, and the Back Arc (Fig. 1). According to Villares et al. (2024), the Volcanic Front is made up of volcanoes that are mostly built on marine bedrock. The Main Arc, on the other hand, is made up of a metamorphized continental basement and is where these magmatic products are found. The Back Arc area is in the Sub-Andean zone and its modern Forearc. It is described by the geochemistry of lavas which are usually high in alkalis (Santamaria et al., 2024). Moreover, there is a pattern of grouping in the volcanic activity along different lengths. This pattern is clearly controlled by the north-south trend of the volcano arcs. Each of these sections is about 50 km long, has its own geological structure, and has a history of eruptions that can be found (Tibaldi, 1992). However, parts of the range like Tulcán, Ibarra (Imbabura crater region), Machachi, and Ambato have groups of volcanoes that are close to each other, with volcanoes being only 7 to 15 km away from each other (Lavenu, Winter, & Dávila, 2020). These groups are made up of several stratovolcanoes and lava dome complexes that explode in different ways and have different chemistry makes-ups. Since these volcanoes are close to each other, their eruptive processes can combine, creating a wide range of volcanic products (Gutscher, Malavieille, Lallemand, & Collot, 1999). Santamaria et al. (2024) say that the eruptive forms of a single cluster depend on things like the magma makeup, the tectonic setting, and the geological past of that cluster. Tectonic processes that go back a long time are also changing this area, as shown by the fact that the Ecuadorian volcanic arc is split into segments. This isn't just a result of differing landscapes. When the Nazca and South American tectonic plates crash into each other, they set off a variety of volcanic events that form different types of cones. For instance, the northern part of this arc, which has volcanoes like Cayambe and Antisana, would have more powerful eruptions than the southern part, which has volcanoes like Chimborazo that are less active or dormant (Barba, Robin, Samaniego, & Eissen, 2008).

### 2.1.2 Typical Varieties of volcanoes

The Ecuadorian volcanic arc is distinguished by the prevalence of medium to high potassium calc-alkaline basaltic andesites to rhyolites, which represent a primary feature of the region (Inguaggiato, Hidalgo, Beate, & Bourquin, 2010). The eruptive products display notable variations, with certain areas exhibiting Shoshonitic rocks, particularly in the back arc setting. The geochemistry of volcanic products in turn provides a record of the complex interactions between subducting Nazca Plate and overriding South American Plate above (Ancellin et al., 2017). These interactions create diversity in eruption types and landforms (Santamaria et al., 2024). The Ecuadorian arc is characterized by the common presence of stratovolcanoes, that are the result of successive eruptions of lava flows, ash, and other volcanic elements (Hall et al., 2004). The region is also recognized for its fields of lava domes, monogenetic cones and collapsed calderas which have been formed by the effects of massive volcanic eruptions. The development of these edifices has frequently been disrupted by sector collapses, resulting in discrete periods of cone formation throughout their eruptive histories (Bablon et al., 2020). The stratovolcanoes Cotopaxi and Tungurahua are renowned in the area according to their symmetrical shapes and regular volcanic activity, since they present, evidences that they have suffered of different phases or erosion and destruction of their main edifices (Ramírez et al., 2022). These volcanoes are frequently associated with violent eruptions that result ash fall and pyroclastic flows (Hall et al., 1999). In contrast, monogenetic cones, which are smaller and typically formed from a single volcanic eruption, are related with various locations within the region (Bablon et al., 2020).

### 2.1.3 Chronology of Volcanic Activity in the Ecuadorian Volcanic Arc

The volcanic history of the Ecuadorian arc is split into three main stages, each with added active volcanoes (Tibaldi, 1992). A developed region with two main stages, first of which is the oldest stage (minimum 2.5 Ma), when activity focused in volcanoes located heavily on volcanic centers along Eastern Cordillera sector to Quito (Alvarado et al., 2014). After this initial phase, a significant spike in volcanic activity occurred around 1.4 Ma. Accordingly, responded formations of new volcanic structures in the Western Cordillera and The Inter-Andean Valley. The youngest phase of volcanic activity, which commenced about 600 ka is recognized by a statistically significant increase in the number of volcanoes active during this period (Barba et al., 2008). It is thought that the increased activity has been put into overdrive due to control of underlying tectonic forces and temperature conditions in the early-forming Nazca crust, leading to generally stratovolcanoes and composite volcanic structures. For example, the historical itineraries show evidence of major eruption in recent centuries for Cotopaxi and Tungurahua amongst other volcanoes (Ramírez et al., 2022).

### 2.1.4 Active, Potentially Active, and Extinct volcanoes in the Ecuadorian Volcanic Arc

The Ecuadorian volcanic arc covers a wide range of volcanoes, which are divided up based on whether they are currently erupting or not; 20 volcanoes, at least in the Ecuadorian Andes, were active during the Holocene (Barba et al., 2008; Hall, Samaniego, Pennec, & Johnson, 2008). According to Borgia, Aubert, Merle, and Vries (2010) and Szakács (2010), an "active volcano" indicates a volcano that has erupted within the past few hundred years. Guagua Pichincha is a typical example of an active volcano. The most frequently active volcanoes in the Pichincha volcanic complex are eruptions between 1999 and 2002, which leave only behind residual clouds (Robin et al., 2010). Another active volcano to note is Cotopaxi, which has seen major eruptions throughout its memory and is regarded as one of the biggest and most active volcanoes in this region (Hidalgo et al., 2018). This volcano has seen around 70 eruptions since 1534, with the eruptive size being rated between 2 and 4 on the volcanic explosivity index (VEI) (Hall et al., 2008). There are signs of unrest or potential eruptions that typify potentially active volcanoes (Pennec, Ruiz, Eissen, Hall, & Fornari, 2011). For instance, Rucu Pichincha is a potentially active volcano. It had an eruption in the past, and its geological constitution suggests that it may erupt again . On the other hand, scale from an extinct volcano these are termed dormant volcanoes and have not had an eruption for a particular duration of time, they are unlikely to erupt once more (Pennec et al., 2011). The best example of this is Chacana, which became inactive thousands of years ago and its last recorded eruption well before then. Furthermore, the

Pululahua volcano – a volcanic dome – though only displaying signs of activity during the Holocene epoch, is classified as a potentially active volcano because advances have been made in recent times (Müller, Cashman, Mitchell, & Vasconez, 2022). Meanwhile, the Cumbal volcano, which straddles the border between Colombia and Ecuador, has also stopped emitting lava for quite a long period (Santamaria et al., 2024). In summary, the Ecuadorian volcanic arc exemplifies a complex and dynamic geological arrangement that has had a decisive impact on its geography at regional and local levels. The division of the arc into several volcanic corridors and cluster units, the variety of volcanic types, and the long tradition of explosive eruptions all contribute to the individual characteristics that form this volcanic system (Bablon et al., 2020; Tibaldi, 1992).

## 2.2 Creating a classification guide

According to the study of the Ecuadorian volcanic arc has, leads naturally to improved geological categorization systems and a clearer picture of the unique geological processes taking place here. Achieving this objective means a comprehensive review of past and present practice so as to determine their merits comparatively, alongside interpretations by participants from different countries. This forms the platform on which continuing research in academic and practical areas may be undertaken. The methodology section starts with a comprehensive analysis of the literature on volcanic stratigraphy. This examines implications for volcanic conditions in Ecuador of previous work in related different geological terrains (Knopf, 2006).

Additionally, this analysis integrates important developments by Cas and Wright (1987) and Smith and Németh (2017), which highlight the need for a coherent classification system to strengthen geological research in the volcanic mapping field. Furthermore, this work uses systematic approaches to selecting and evaluating literature, guaranteeing that only the most relevant research has been considered in the proposed classification-categorization system. The research seeks to develop it in conformity with international standards. The classification developed in this work should be adaptable in advancing the field of volcanology - particularly in the dynamic and complex environment of Ecuador's Quaternary Arc (Barberi et al., 1988; Georgatou, Chiaradia, Rezeau, & Wälle, 2018; Lavenu et al., 2020).

In order to reach the targets, the current literature on volcanic stratigraphy is analyzed widely, paying particular attention to works relevant to and practicable in the peculiar volcanic conditions of Ecuador. The purpose of this review is to fix a set of principles for choosing case studies according to internationally accepted standards or models. After that, this approach will be applied to specific case studies to assess its efficacy and utility in describing the volcanic deposits of the region. The subsequent sections will provide further elaboration on this technique, presenting a comprehensive and rigorous methodology that contributes to the advancement of volcanology, particularly within the dynamic and diversified context of the Ecuadorian Quaternary Arc (Fig. 2.1).

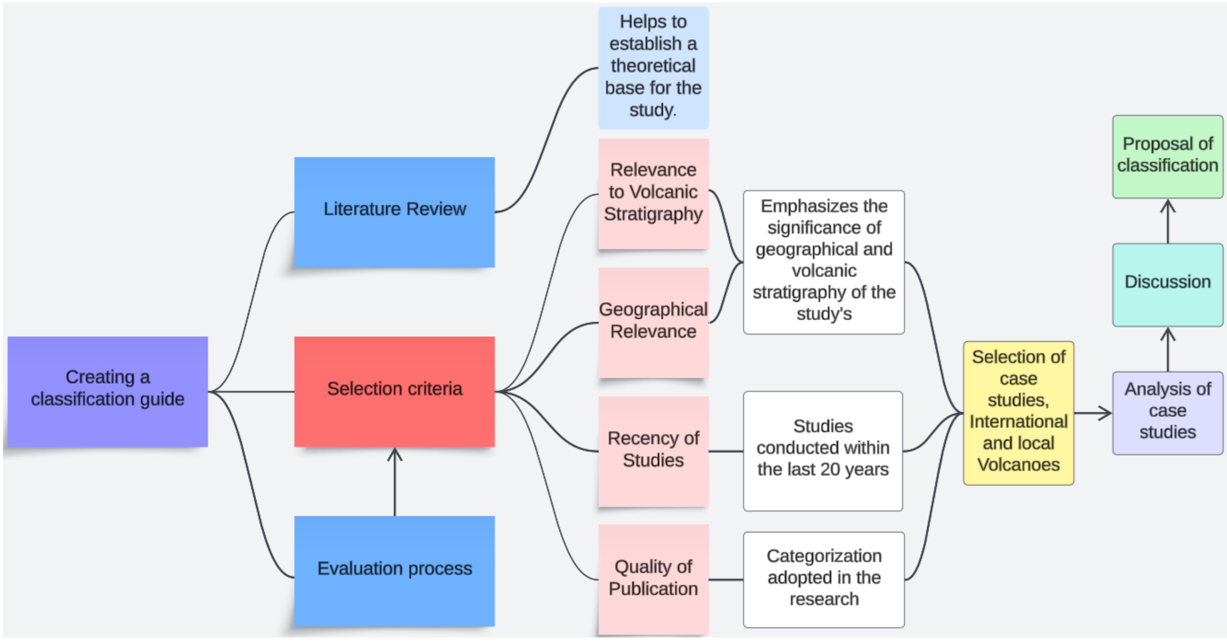


Figure 2.1: Flowchart, process flow diagram to create a classification guide

### 2.2.1 Literature Review

Developing a literature review means evaluating written works or manuscripts on a topic. For postgraduate students and lifelong academic researchers, conducting literature reviews regularly is one of the basic procedures in academic activities. This technique itself is of considerable importance in the selection of a theoretical framework. In addition, a review of the literature helps establish a theoretical base for the study (Knopf, 2006). It assists in formulating research questions duties it otherwise performs in an all-too-mechanical manner. This review of the literature focuses on the research questions so that it is possible to move step-by-manageable-step through the rest of the research process (Templier & Paré, 2015). Given the numerous skills that undergraduate students, are required to master such as critical reading and writing, note-taking, time management skills and how to undertake extended searches of academic databases and referencing, it is clear that students need support in conducting effective literature reviews. In this publication, offering concrete advice may greatly help undergraduate students complete the literature review phase (Snyder, 2019).

### 2.2.2 Selection criteria

Volcanic stratigraphy is closely related data collection and volcano mapping, combining lithostratigraphy with other stratigraphic units. This approach allows to create geological maps that record volcanic activity (Pioli, Melis, & Mussi, 2023; Szakács, 2010). Uniform classification systems are key for correlating volcanic areas and using precise terminology (Cas & Wright, 1987; Martí, Groppelli, & da Silveira, 2018; Smith & Németh, 2017). Recent studies prioritize updates to Ecuador's national geological maps, revealing the current standards are inadequate for Quaternary volcanic deposits (Albán, 2019; Hall et al., 1999). Geographically, the research focuses on Ecuador's Quaternary Arc and compares it to global volcanic regions, proposing a classification framework (Newhall & Hoblitt, 2002). This methodology emphasizes the significance of geographical and volcanic stratigraphy in relation to the study's importance, the quality of publishing of the categorization adopted in the research, and recency, which regards to studies conducted within the last 20 years.

#### Relevance to Volcanic Stratigraphy

Researching volcanic stratigraphy should be given high importance. Specifically, the examination and categorization of layers and beds. In the field of volcanic areas, volcanic stratigraphy is a focal point of data collection from field research. (Pioli et al., 2023). Currently, there are ongoing discussions among researchers about its use for volcano mapping. Volcanic stratigraphy uses lithostratigraphies in combination with other stratigraphic units, such as biostratigraphic units or syntectonic units. Such use is vital because the geological map provides the basis for any comprehensive study of volcanology and contains objective records of what really happened during eruptions, interspersed activity periods, etc. (Szakács, 2010). Exploring volcanic stratigraphy and how stratigraphic mapping has been done gives fresh insights and constraints about volcanic dangers; it helps on discern characteristics related with volcanology, petrography, geochemistry and petrology; and it allows to develop geophysical models for geological surveying (Joan Martì Groppelli, 2013).

### Quality of Publication

This article focused mainly on the stratigraphy of volcanoes. First, research focused on the Quaternary arc of Ecuador and other volcanic arcs worldwide. Geologic studies need to employ uniform classification framework for comparison and communication between scholars' work (Martí et al., 2018). According to Cas and Wright (1987), a uniform classification system for volcanic deposits aid correlation between volcanic areas. Smith and Németh (2017) also vocalize the need for exact terminology when identifying volcanic deposits. The quantity and quality of publications were moderately associated, and there was an interaction effect. Quantity had a greater influence than quality. Authors who valued quality above quantity had strong associations with prestigious universities (Haslam & Laham, 2010). This would favor clear volcanic stratigraphic classification criteria for Quaternary Ecuador. it also is a more logical division of volcanic stratigraphic units. Uniform standards help match data between sites, and for geological purposes. The number of publications and their impact were positively associated. However, it was quality that really mattered. Prestigious institutions emphasized quality.

### Recency of Studies

In order to keep abreast of the latest tools and experimental results, this review gives priority to material published in the last 20 years. The collection does, however, also include some classics that must be addressed: the great works in every field are influential regardless of when they were published. Nevertheless, the established national standard in Ecuador, as set by the *Instituto de Investigación Geológico y Energético* (IIGE), is clearly unsuitable for Quaternary volcanic deposits. Based on the composition of volcanic units and characteristics that can be seen either in cliff outcrop or in association with the volcano, thus something is called inland. The difference with this system sets a common name for cross-referencing studies and insists on making it available as a guidebook. The principle is also appropriate to update the part of this information contained within maps published as recently as 2015 (Albán, 2019; Murphy & Salvador, 1999). Nonetheless, although this method is valuable in some cases, it does not do justice to the vast array of information available on volcanic geology in this area (Hall et al., 1999)

#### Geographical Relevance

The focus in this research is the Ecuadorian Quaternary Arc, with comparisons to the Andes, Pacific Ring of Fire, and Galápagos Islands. This method consolidates up-to-now data into a complete volcanic unit classification framework. A scheme such as this will allow us to revamp the present classification of these units. Moreover, following international standards, it formally organizes volcanic units for the first time. Comparisons between Nicaraguan, USA and Italian proposals are also brought together, the goal being to provide an integrated scientific plan suitable for Ecuador's terrain. The paper investigates how such a technique well fits specific geological conditions and for example updates B. Bernard and Andrade 1:500,000-scale volcanic maps of 2011 titled *Mapa de los Volcanes Cuaternarios del Ecuador Continental*. Important aspects to be considered in these changes are volcanic type, structural traits and eruption history. A uniform categorization system may improve volcanic eruption prediction and risk reduction. In order to predict future volcanic activity, it must be understood the trend in historical eruptions (Newhall & Hoblitt, 2002). By utilizing a reasonable system of categorization, the geological community can better grasp all of the previous volcanism at the same time as predicting what may yet come its way.

### 2.2.3 Evaluation Process

This subpoint introduces an evaluation protocol created to increase the completeness and reliability of literature reviews in Information Systems IS (Templier & Paré, 2015). The Templier and Paré review highlights the importance of a rigorous, explicit methodology for conducting systematic literature reviews. This is a main point, yet one that often gets missed too easily among researchers. In this part of the research project, believe in presenting an accurate and systematic method on how we assess review papers applied within a proposed evaluation framework (Webster & Watson, 2002). By framing their critique of existing reviews within the context of a systematic review approach, this direction helps them identify how previous works are missing and also directs researchers in making sure that any new scientific synthesis is methodologically solid.

### 2.2.4 Selection of case studies on Ecuadorian volcanoes

Locally focused on the volcanoes Antisana, Pichincha, Tungurahua, Cotacachi, and Imbabura, which are some of the most important in Ecuador due to their long eruption history and studies performed about them using a variety of instruments making this contribution with up-to-date-results giving an insight into behaviors as well as volcanic characteristics. On the other hand, this study considers data extracted from prominent volcanoes around the world having databases of broad coverage and acknowledged internationally—to get an even deeper perspective in the comparative analyses on Mount Saint Helens, Mount Etna, Nicaraguan Volcanic Chain (NVC); the Trans-Mexican Volcanic Belt. These case studies have been widely studied in the last years so, the information is valuable to develop this proposal. In these studies the authors have used several instruments such as:

- Geological Field Surveys
- Stratigraphic Logging
- Petrographic Analysis
- Geochemical Analysis
- Radiometric Dating Techniques
- Geological Mapping
- Lithostratigraphic Classification

The wide database of these volcanoes can be useful for the final interpretation in terms of stratigraphical units and classification within a Quaternary volcanic arc from Ecuador.

# Chapter 3

# Results

## 3.1 Classification and characterization schemes used in representative volcanoes worldwide

### 3.1.1 Nicaraguan Volcanic Chain Map Analysis

In order to analyze the volcanic chain of Nicaragua, the article by Hradecký et al. (2006)was considered. From this source, the following information was extracted. Comprising a range of volcanoes along the coast from Mexico to East El Salvador shown in Figure 3.1, the Central American volcanic front is a broad geological feature. 18-volcanic-center from Nicaragua volcanic front highlights the dynamic interconnections between volcanism and tectonics; eight of the eight presently active volcanoes there are Middle Miocene underlies the area to Late Pliocene volcanic and associated volcanogenic deposits building the caldera at San Pablo, with different formations including Coyol and Tamarindo Formations that add to the variety of rock systems in this area. Usually, a few tens of kilometers across, the young volcanoes are arranged in central clusters separated by sinistral strike-slip faults that define the limits between various volcanic complexes (Fig. 3.1), including Pico Duarte, where such fissures have been documented previously. By means of in-depth fieldwork, this study clarifies the geological processes forming, evolving, and rising to the volcanism of this volcanic front, therefore enabling us to assess its unique features disclosed during our investigation (Hradecký et al., 2006). The Czech Geological Survey (CGS) and

Nicaraguan INETER cooperated in the mapping of geological geomorphological maps from 1997 to 2001 along the entire seismic lineation. Writers then took a formulaic approach to exploring those volcanic systems and engorged extensive field research. This required several years of geological mapping, stratigraphic study, and sample collection at various sites with volcanic deposits in order to understand their lithology, composition, and age properly. The scientists used radiometric dating methods to determine the periods of volcanic activity, allowing them to connect multiple ancient volcanic units and ascertain their rock variety. The authors also conducted geological mapping. The researchers also conducted geomorphological investigations to determine how volcanic and tectonic processes altered the landscape. By blending geological and geomorphological data, scientists produced a pair of maps that complement each other. What we see is the geology map shows things under the ground and what has historically occurred with volcanoes. In contrast, the geomorphological Map depicts surface features as well as how those have changed over time. This detailed procedure helps us to comprehend better the natural significance of volcanism within the Nicaraguan Volcanic Chain, enables a finer paleovolcanological estimate of volcanic risk and provides information for land use planning in our case (Hradecký et al., 2006).

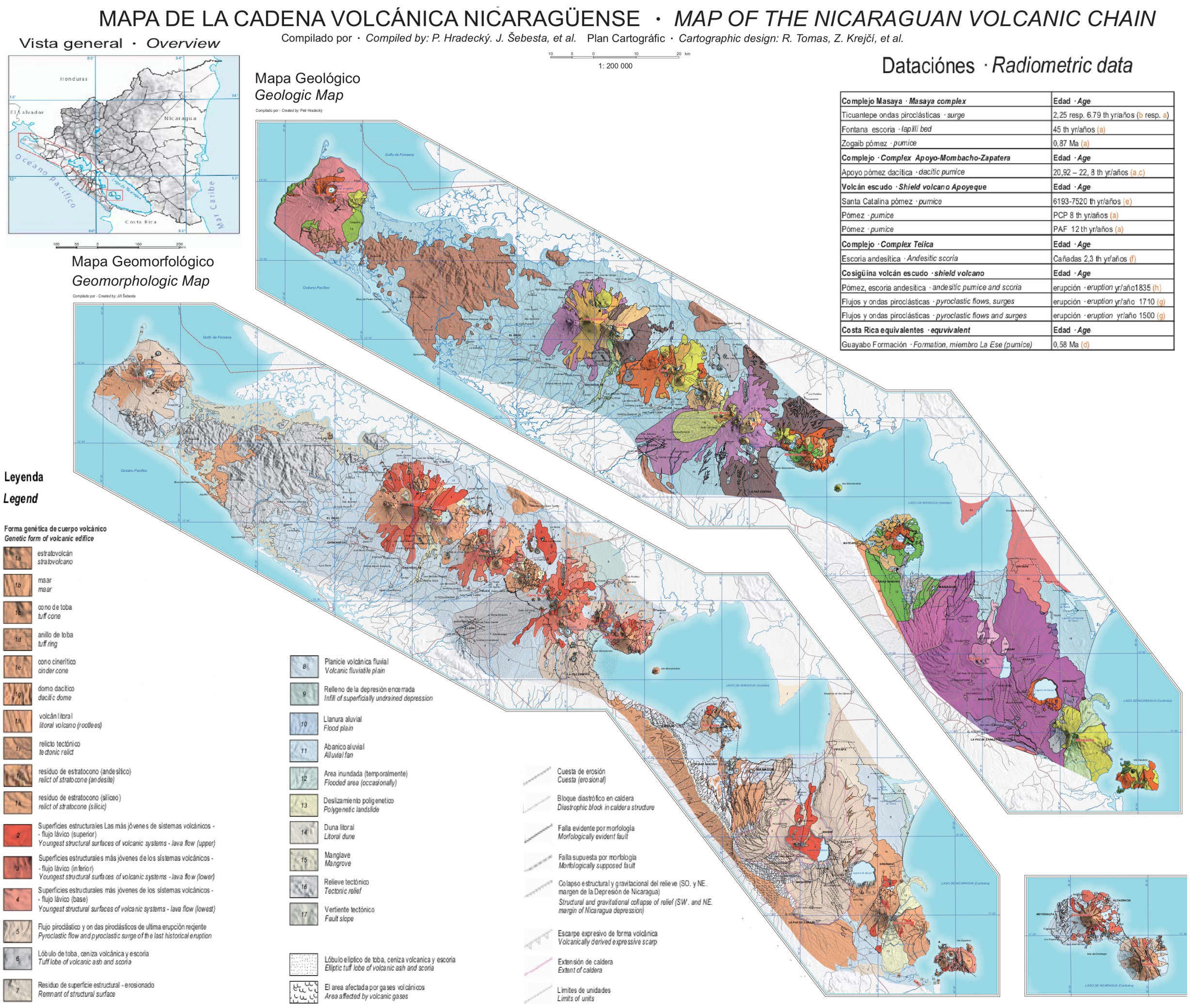


Figure 3.1: Geologic and Geomorphologic Map of the Nicaraguan Volcanic Chain. (Modified from: Hradecký et al. (2006))

### The Nicaraguan Geologic and Geomorphologic map

The research found that geologic characteristics which provide cues about eroding and building processes. There are other important aspects that the geology map can explain, such as how rock layers lie next to one another or what their composition is, and even the deposits produced by volcanoes. Using its chemical constituents, ages, and how they erupted (style) in the past, it categorically groups them as well. The geomorphological map, in contrast, reveals the various landforms of Earth's surface, such as caldera, shield volcanoes, ignimbrite shields, and stratocone / composite or stratovolcanoes. These features were developed by erosion, weathering, and sedimentation, which are continuously active processes. The objective of this study is to provide the public with a clearer explanation of how natural processes are linked to changes in landforms. To assist with this, we split the data into two different maps. Clustering these kinds helps make it easy for a person to check out the volcanic scenery in more detail and get hyperlinks between rock layers beneath as well around what people spot(Hradecký et al., 2006).

**Representation of volcanic units**

The volcanic units have been extensively studied, including geological studies and sediment analysis around the Nicaraguan volcanic chain. Numerous volcanic systems and structures have been discovered in the area. All are characterized by their geological features and volcanic activity. There are groupings of volcanic blocks based on a number of factors, ranging from the rock types they contain to numerical ages for formation to how different ones are stratigraphically related within sections. Cosigüina shield volcano, San Cristóbal-Casita complex; Telica complex, El Hoyo-Cerro Negro complex; Momotombo-Malpaisillo-La Paz Centro complex; Apoyeque shield volcano), Miraflores-Nejapa volcanic-tectonic zone (part of the Nejapa-Polvorín range); Masaya volcanic complex): Virgen-Utlatán and Cerro La Mula-Escoria cones: Granada perilacustrine graben volcanoes) Apoyo/Mombacho/Zapatera volcanic complex Nandaime-Granada chain on slip faults in grabens Ometepe Island forests. The same volcanic units are then subdivided by the different types of deposits they contain, such as pyroclastics, lavas, and lahars. They are analogous in process, composition, and age. Stratigraphic studies can also identify different rock layers within volcanic formations, including the various basal ignimbrites, silicic ashfall tuffs, bedded pyroclastic deposits, and many categories of lava flows(Hradecký et al., 2006).

### 3.1.2 Analysis of Volcanic geology of the easternmost sector of the Trans-Mexican Volcanic Belt, Mexico

To examine the Trans-Mexican Volcanic, the paper by Carrasco-Nuñez et al. (2017); Carrasco-Núñez et al. (2021) were utilized. The easternmost part of the Trans-Mexican Volcanic Belt (TMVB) is a region whose geology contains several types of volcanic rocks and has a long geological history.

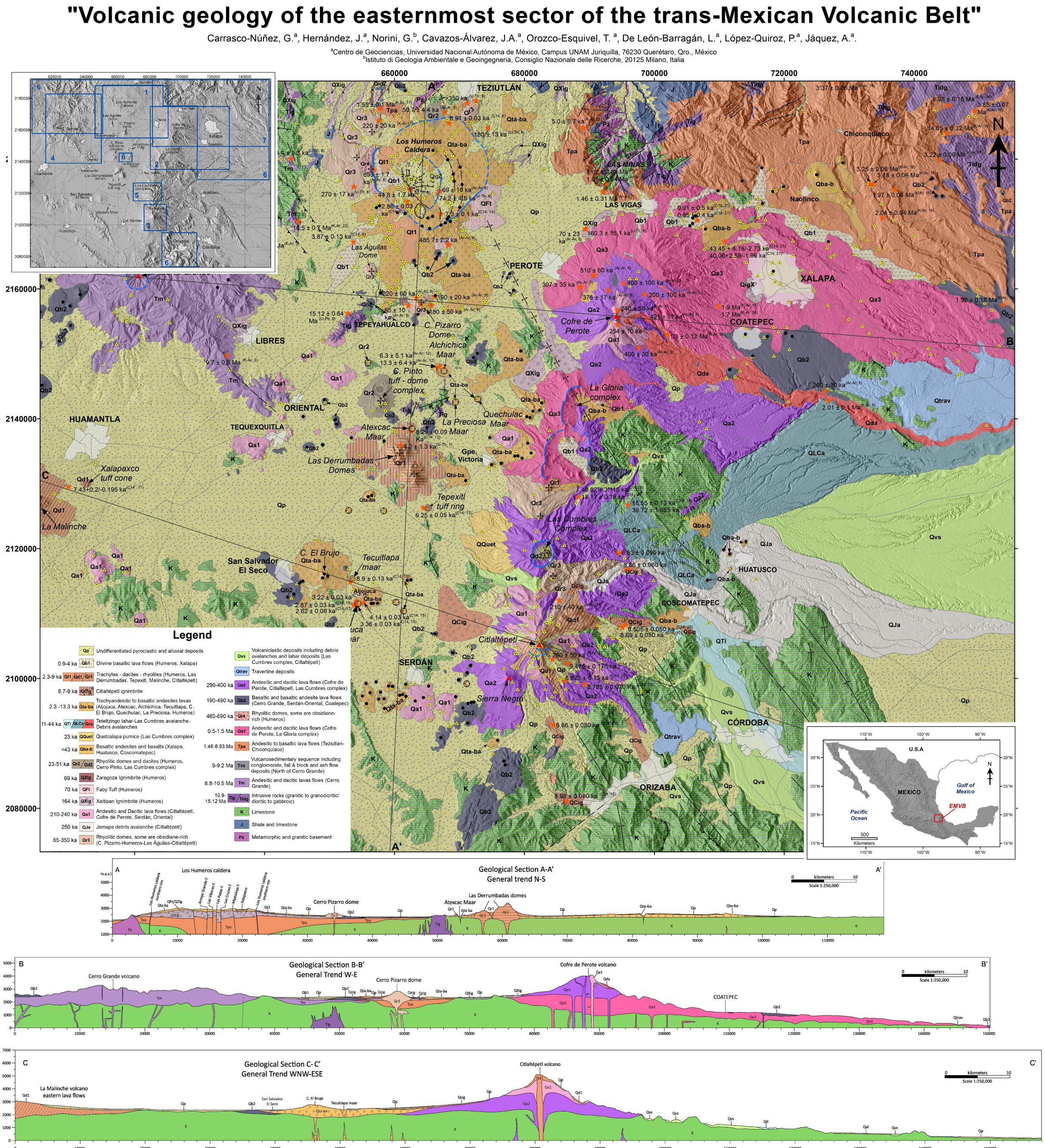


Figure 3.2: Volcanic geology of the easternmost sector of the trans-Mexican Volcanic Belt (Modified from: Carrasco-Núñez et al. (2021))

The article by Carrasco-Núñez et al. (2021) was mainly considered in order to analyze the Mexican Volcanic Belt. This region includes two different volcanic areas: the Serdán Oriental Basin (SOB) and the Cofre de Perote-Citlaltépetl Volcanic Range (CPCVR). For example, the rocks in this region have been formed since time immemorial, such as during the Paleozoic era (around 541 to 252 Ma), when metamorphic and sedimentary rocks were formed. Then, in the Mesozoic Era (about 252 to about 66 Ma), another layer of earth was added. Many of the world's volcanoes have been active since about 66 Ma, the so-called Cenozoic Era. Divided by the Quaternary period of active volcanoes, we finally enter our desired era. This has also led to the formation of a variety of exclusive landforms, some derived from common single-gene features such as cinder cones, maars, and tuff rings. There has also been a large number of large stratovolcanoes formed; some examples are Citlaltépetl (5,636 m), the highest peak in Mexico; volcanic activity through this area has made many deposits: lava flows, pyroclastic flows, and lahars. These deposits, including strata of pyroclastic layers and various lava flows, show the geological processes that took place (Carrasco-Núñez et al., 2021). The methodological framework applied to the volcanic geology of the eastern area of the Trans-Mexican Volcanic Belt was a comprehensive approach combining detailed fieldwork, geological mapping, and geochemical analysis. The team conducted an initial round of extensive fieldwork to inventory the various volcanic structures and lithological units that populate our study area. Handheld GPS is used extensively to ensure accurate recording of the geographic coordinates of geological samples and significant volcanic landforms. The team collected existing geological maps and used Google Earth satellite imagery to enhance their understanding of the geography and geology within various parts of the place. The first step was to create a 15 × 15 m resolution Digital Elevation Model (DEM) using data from the Nehy Mexican land cover source. The volcanic terrain itself is represented by the frame. For the 61 new studies, representative samples were selected for petrographic and geochemical characterization. In total, data from 550 literature-based observations were supplemented by this research effort. Gates used 104 isotopic ages from all dating methods to construct a regional chronostratigraphy. A systematic approach facilitated the recognition of individual lithostratigraphic units and the construction of an integrated regional-scale lithostratigraphic column. This ultimately provided insight into the volcanic geology of this dynamic region (Carrasco-Núñez et al., 2021).

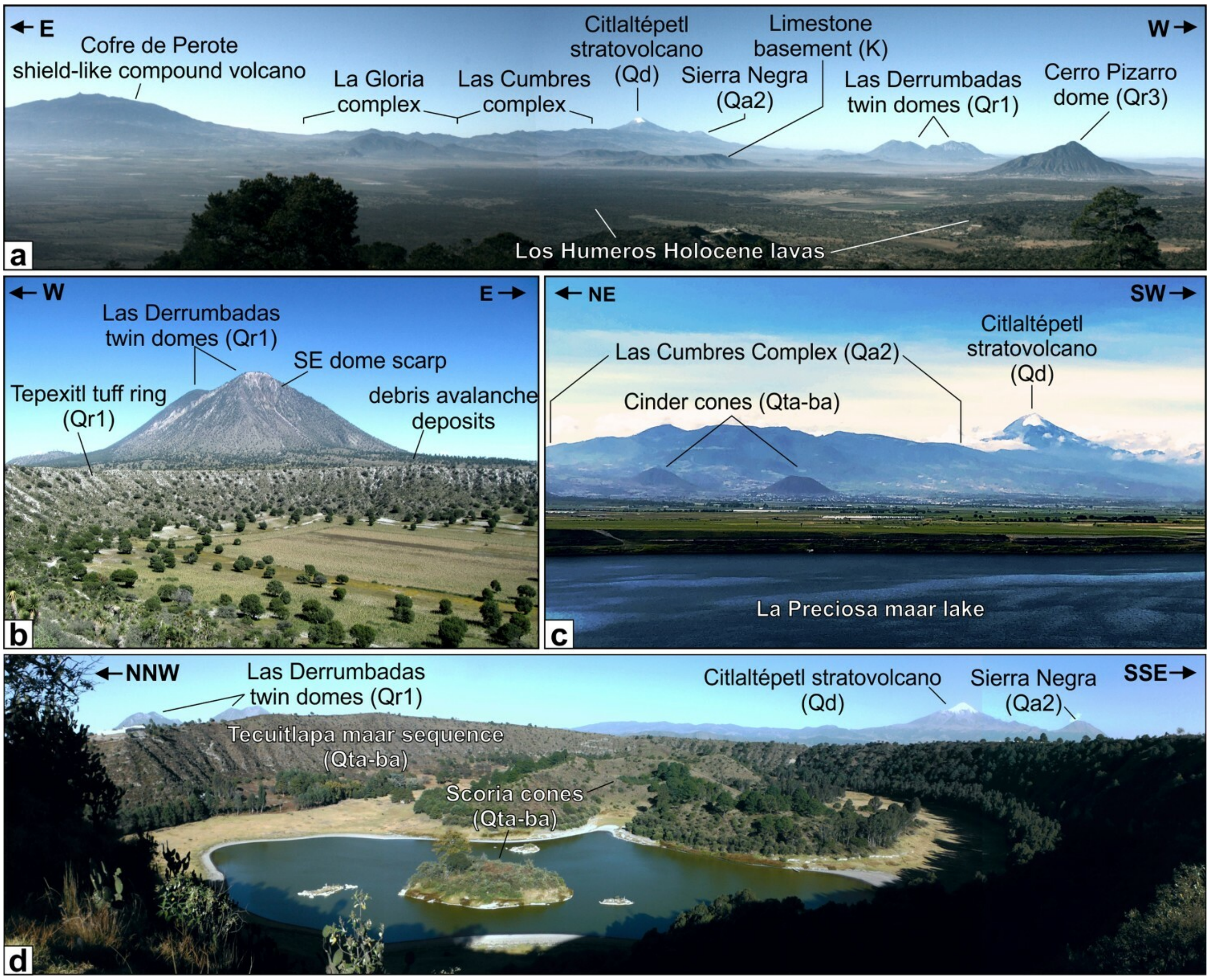


Figure 3.3: Distribution, chronostratigraphy, and composition of the main volcanic units at TMVB. (Taken from: Carrasco-Núñez et al. (2021))

### Representation of volcanic units

According to the researchers, there is a great diversity of cones in this easternmost part of the Trans-Mexican Volcanic Belt. Geologists have classified these formations into distinct lithostratigraphic groups. This study examines the following factors/characteristics:

- The basaltic andesitic subvolcanoes are also known for their explosive eruptions that form maars. Alchichica, Aljojuca, Atexcac, Tecuitlapa, and Preciosa are the sites that best fit these cartographic attributes.

- Cinder cones and lava cones is produced by relatively small amounts of volcanic material that accumulate around a single vent. A good example of this is El Brujo, which is famous for having its port.

- Another natural feature of great local importance are the dome-shaped rhyolitic rocks, which include Cerro Pizarro and Las Derrumbadas.
- Tuff rings are geologic rocks formed when volcanoes have violent eruptions. Two prominent tuff rings are Cerro Pinto and Tepexitl.
- Los Humeros volcanic complex has a high level of activity and is considered the most important caldera in the TMVB.

Stratovolcanoes have an upper central volcano with several cool ridges wrapping around it (Fig. 3.3). The CPCVR are mostly large, complex polygenetic volcanoes composed of rocks ranging from andesitic to dacitic (wouldn't need this). They include the shield-shaped Cofre de Perote volcano, along with complexes such as La Gloria and Las Cumbres, and the active Citlaltépetl stratovolcano (Pico de Orizaba). Some volcanic events were explosive, as evidenced by pyroclastic deposits, block and ash flows, ignimbrites, fallouts and surges (Carrasco-Núñez et al., 2021).

### 3.1.3 Analysis of Mount Saint Helens volcano

To study Mount Saint Helens volcano, the paper by Gabrielli, Spagnolo, and Siena (2020) was studied. Mount St. Helens is a stratovolcano with a volcanic history that extends back over 40 ka. This history is linked to the Pleistocene period, which occurred between approximately 2.6 Ma and 11,700 ya (Fig. 3.5. The most notable and well-recognized event occurred during the Holocene era, namely during the catastrophic eruption in 1980, which had a profound impact on the volcano's physical features and the area surrounding it. The volcanic activity at Mount St. Helens provides an explicit example of the continuous geological processes that continue to pose threats in the present day. Mount St. Helens, a stratovolcano situated in the Cascadia volcanic arc, has achieved a certain degree of notoriety as a result of its 1980 eruption, which resulted in significant alterations to its physical characteristics and the surrounding areas. This study presents comprehensive cartographic representations of the geomorphology and surface geology of Mount St. Helens. The maps were created using a variety of data sources, including high-resolution digital terrain models, LIDAR data, Google Earth images, geological data, and field surveys. The maps in question are available in two scales: 1:50,000 and 1:25,000. The geomorphology of the region has been significantly impacted by the 1980 eruption and the extrusion of the dome in 2004, which has had a notable influence on the major glacier situated within the crater (Gabrielli et al., 2020).

A systematic approach to fine-scale mapping of the volcanic deposits at Mount St. Helens was used, emphasizing the topography and surface geology of the volcano. The landforms of the area were classified into two groups: endogenous (volcanic) and exogenous glacial, fluvioglacial, and gravitational landform types. This classification method was used to capture all the different geological characteristics in this part. This contrast was used to demonstrate the diversity of volcanic structures and their interactions with landscape-forming exogenous forces (Gabrielli et al., 2020; Hausback, 2000).

The authors took their research a step further by classifying volcanic landforms according to their association with the 1980 eruption. The authors applied a binary classification technique to pre-eruption and post-eruption categories to evaluate how the landscape was altered by this natural disaster and to assess the geomorphic evolution of Mount St. Helens after such a catastrophic event. The temporal sequence of events provided critical information on how the volcanic landscape evolved with changing directions of volcanic activity (Gabrielli et al., 2020; Lipman, 1981).

Fieldwork provided validation of the mapped features; several points on the map were confirmed in person over two weeks. The researchers also used ground penetrating radar (GPR) to scan specific locations in the volcanic region, such as post-explosion craters. It opens a new window for understanding the properties below the surface and helps decipher what we observe on the ground in California (Gabrielli et al., 2020; Hausback, 2000).

ArcGIS software was used to analyze and compile the research data discussed above. ArcGIS is a great way to create maps and make spatial queries when you have access to other map layers or when it helps to communicate increasingly large amounts of information; this type of tool related to GIS - Geographic Information Systems can be very useful. Field observations, magnetic surveys, and state-of-the-art maps have also been used by researchers so that the surface geology and geomorphologic process at Mount St. Helens can be completely determined (Hausback, 2000).

### Representation of volcanic units

There are thousands of different types of endogenous volcanic features that can be seen in the greater Mount St. Helens area that tell us about its geologic past, eruptions. The shape of the volcano is quite obvious in its form, and this distinguishes this area, as Gabrielli et al. (2020) points out.

**1. Crater:** The summit and central part of Mount St. Helens, where the main crater is located, have changed dramatically from previous eruptions in 1980 - like this dome building eruption - to nearly a decade after May-August 2004.

**2. Volcanic domes:** The main volcanic formations of Mount St. Helens consist of volcanic domes, showing a diverse range of eruptive patterns and durations that have taken place over a period of time.

**3. Volcanoes:** Volcano types produce different volcanic products (pyroclastic flows, lava flows, and other deposits) and inferred timing of activity.

**4. Unique eruption morphologies:** The 1980 eruption was atypical because most of these features form only during single eruptions, such as debris avalanches, hummocky deposits, and secondary explosion pits.

Lipman (1981) Summary of geology and volcanic stratigraphy at Mount St. Helens eruptive history in general as is shown in Figure 3.4, collectively logs from four common types of Quaternary rampart terraces erupted as pillow flows or pyroclastic flow deposits before and after their conversion to lava domes with compiled maps help illustrate the developing activity. Mount St. Helens volcanic rocks have been classified into groups by lithological, mineralogical. Fortunately, most of the volcanic rock hand samples group well (percentage squares plotted on predefined areas). Ferromagnesian minerals: These links form a suite of ferromagnesian minerals that reflect each eruptive phase. Wood samples found in the layers are also radiocarbon dated to further aid in differentiation. Grouping these layers into sets representing different eruptions provides a geologic chronology of the area, allowing sequential sequences of activity to be identified. This approach makes it easier to identify different volcanic types based on composition, age, and other characteristics (Gabrielli et al., 2020; Hausback, 2000).

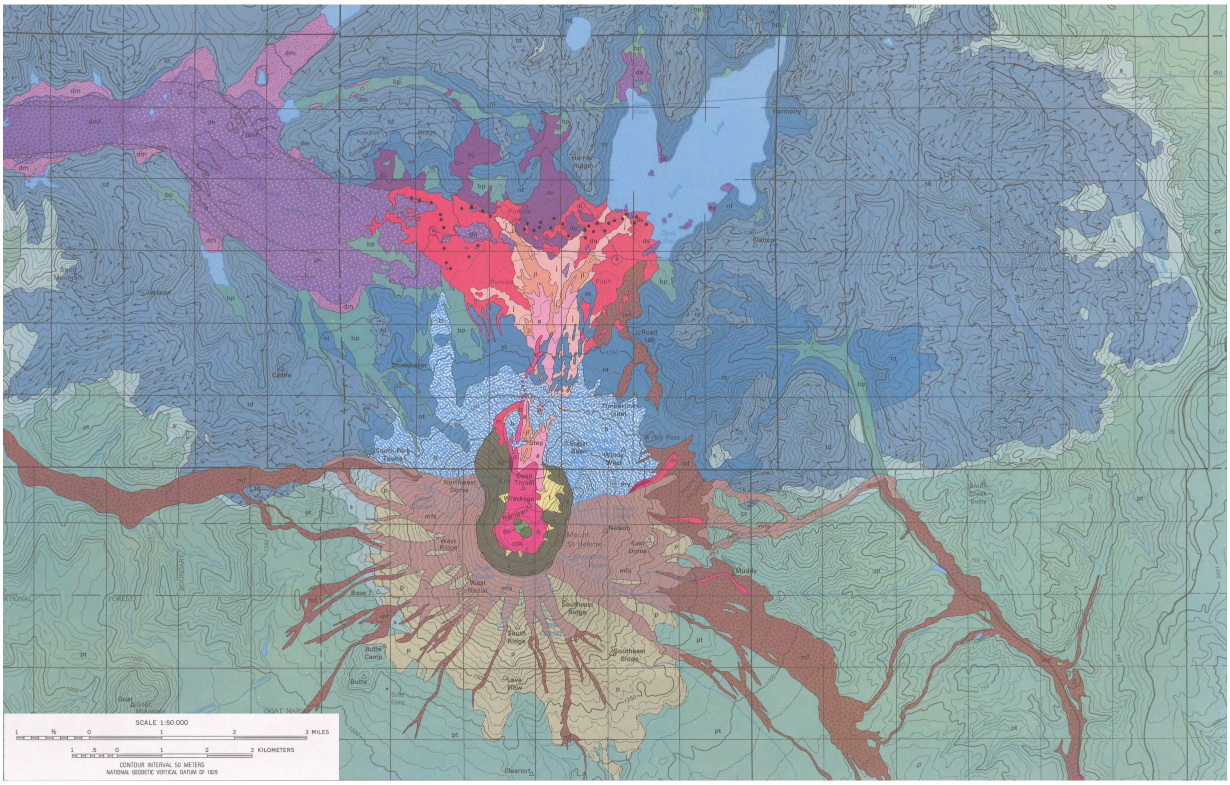

Figure 3.4: Geologic map of proximal deposits and features of 1980 eruptions of mount st. Helens, Washington. (Modified from: Lipman (1981))

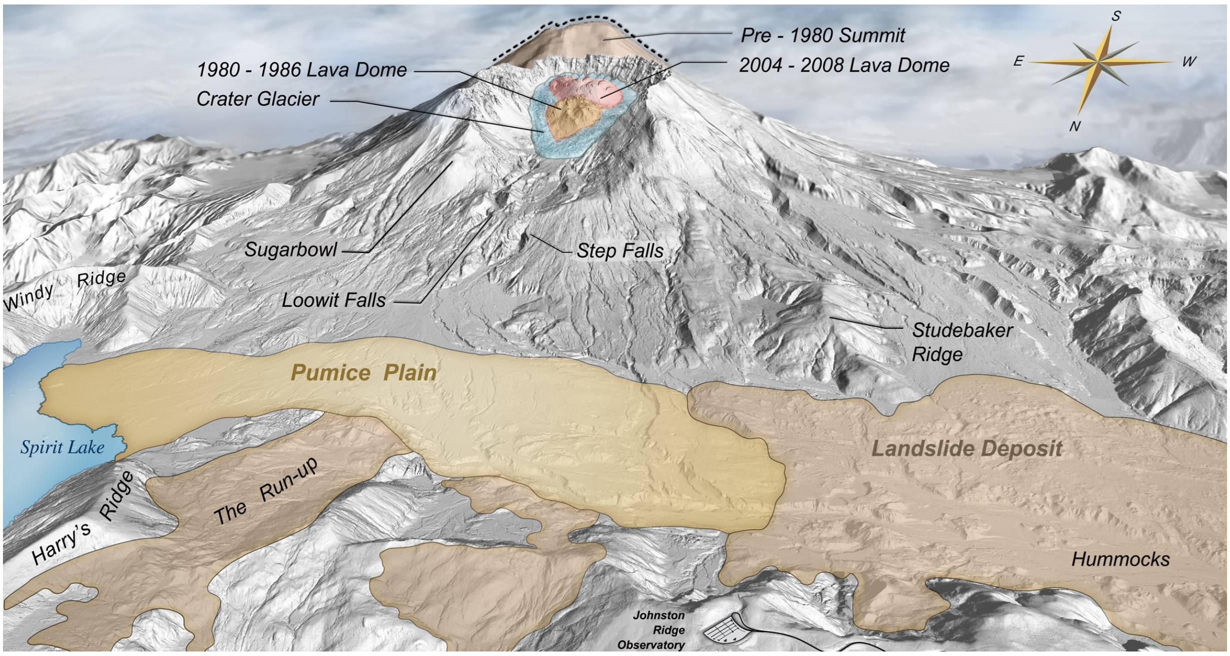


Figure 3.5: LIDAR-derived shaded relief map of Mount St. Helens showing post-1980 eruption topographical features, including lava domes and landslide deposits. Adapted from Dzurisin et al., 2013.

### 3.1.4 Geological map of Etna volcano

The mountain that features in the myth of Ceres and Proserpine, Sicily (Now showing: Mount Etna; Location: eastern coast of Sicily-Italy). It remains one of the most active volcanoes in the world with records from the late Quaternary period to the present. Over the last half million years, this stratovolcano has also experienced a series of catastrophic explosions that have shaped it into its present form. Moving lava and explosive pyroclastic deposits can be sent flying during these events. Recent geological mapping has revealed that there are 27 distinct lithostratigraphic units (Fig. 3.6. They have been grouped into eight synthems and then combined into four supersynthems. This method of categorization is evidence of Etna's complex volcanic history. The groups were created using radiometric dating and meticulous field studies. They provide a precise punctuation of the volcanic sequence. Following a study of geological maps, the most detailed data have been gathered by painstakingly reconstructing ancient volcanic eruptions. We limited our analysis to the Holocene eruptions of Etna (Branca, Coltelli, Beni, & Wijbrans, 2008; Branca et al., 2004; Branca, Coltelli, Groppelli, & Lentini, 2011).

The geological map of Etna shows that the lithostratigraphic groups are grouped by their own mineralogical and petrographic characteristics (mineralogy, texture, and colors). This knowledge of the layering between lithostratigraphic groups provides us with a distinct potential to know how and when volcanic events occurred and took place in geologic time at Etna(Branca et al., 2011).

This study allows us to study the depositional process and to identify the volcanism that occurred in the past. The volcanic sequence shows where the boundaries are between lithostratigraphic units, which define them as separate groups due to unevenness. These surfaces provide times when erosion took place in the past, nor are they complete rock records. The shape and structure of the field can identify what type of eruptive center this would be. It helps us understand how volcanic activity is structured in a 3D space inside the volcano. We have to spend a tremendous amount of effort in the field, and detailed stratigraphic logging is used to figure out where these lithostratigraphic units are within the cycle. From there, we investigate how they correlate. They are easy to identify because the field log data are readily available (Branca et al., 2011).

In their geological study of Mt. Etna, the authors organized the stratigraphic structure and geological interpretation using the terms lithosomes/synthems/supersynthems.

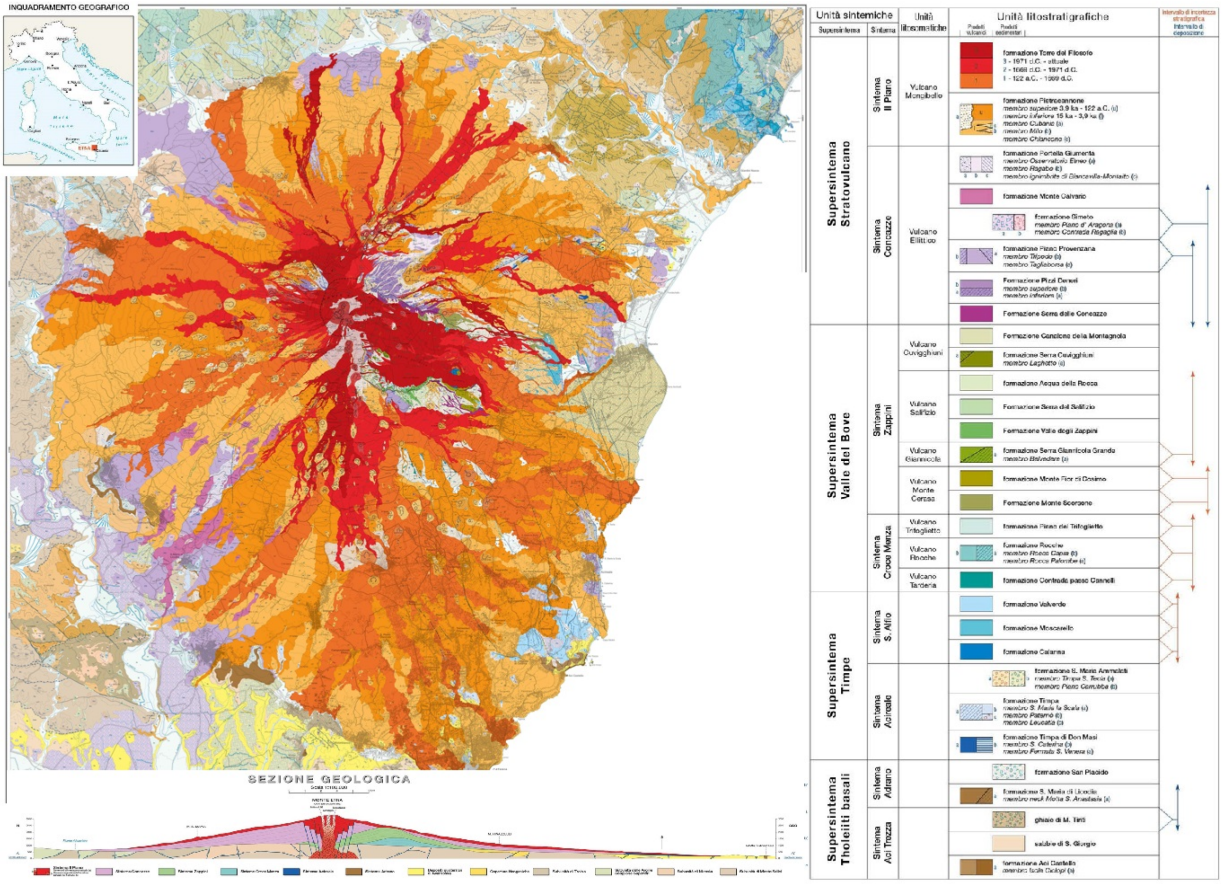


Figure 3.6: Geological map of Etna volcano (Modified from: Branca et al. (2004))

### Representation of volcanic units

The authors discovered the volcanic units near Etna volcano using a variety of different principles and metrics. They typically distinguish between the different volcanic units using lithostratigraphy. This involves a detailed study of lithological features such as mineral type, consistency, and color. The volcanic process of Etna is detailed by these authors using lithostratigraphic units belonging to a variety of ranks, referred to in this paper as formations, members, and flows. These units are defined mainly by their lithological character (Branca et al., 2011).

While in the field, the surveyors of this new study team will conduct detailed geologic surveys and record entire stratigraphic sections as they determine where each lithostratigraphic unit is located. This research is designed to determine the relationships between different suites and to build a comprehensive picture of the natural environment of this region. The authors also work on this type of samples with laboratory techniques such as the study for concrete blocks, along with petrographic research or after geochemical and radiometric dating. These studies have provided a picture of the age, composition, and growth history of the volcanic rocks, and have allowed lithostratigraphic units to be more precisely defined (Branca et al., 2004).

## 3.2 Classification and characterization schemes used in representative volcanoes of Ecuador

Widespread, the authors consistently follow established protocols and criteria for identifying official and informal lithostratigraphic units in accordance with the recommendations put forth by Murphy and Salvador (1999). The authors use a methodical and thorough methodology to identify the units of volcanic material around the Etna volcano. This involves combining observations made in the field with precise investigations conducted in the laboratory. By doing so, they are able to establish a dependable description of these volcanic units.

### 3.2.1 Analysis of The Cotacachi - Cuicocha volcanic complex

This analysis in mainly focused on the publications developed by (M. Almeida, 2016; M. Almeida et al., 2023; Sierra et al., 2021). The Cotacachi-Cuicocha Volcanic Complex is a notable geological formation situated in the northern region of the Andes in Ecuador in the Imbabura UNESCO Global Geopark in Ecuador at coordinates 0.361°N and 78.349°W. It is known for its stratovolcano and the accompanying caldera. The central building of the complex is the Cotacachi volcano, with a maximum summit elevation of 4,939 masl. This complex spans approximately 268 $km^2$ (Merizalde, Ubidia, & Ruiz, 2022) (Fig. 3.7). The Cotacachi stratovolcano is estimated to have initiated its formation during the Middle Pleistocene epoch, approximately 173 $\pm$ 4 ka, and has subsequently undergone multiple stages of activity. The Cotacachi volcano is considered an extinct stratovolcano. Evidence suggests two significant debris avalanches during its evolution: the first occurred between

162 and 108 ka, and the second avalanche occurred between 102 and 65 ka (M. Almeida, 2016). The southwest Muyurcu dome was formed approximately 138 ± 4 ka, followed by the eruption of the Verde Tola unit lavas, which were dated to a range of 113 ± 6 ka to 133 ± 9 ka. Following a period of quiescence, the Cotacachi stratovolcano underwent a renewed phase of development between 122 and 108 ka, resulting in the extrusion of additional lava flows (M. Almeida et al., 2023)). During the Upper Pleistocene, this volcanic complex was active at least twice. The earliest movement occurred between 70 and 60 ka, with the Piribuela dome extruded around 65 ka. The Cuicocha pre-caldera domes are the product of this second period, dating to less than 10 ka. Cuicocha caldera is currently filled with water: In what is believed to have been a large eruption about 2980 ± 30 ya, the upper part of Cotacachi was opened, and a rift caused the landslide and collapse on its eastern side, forming Cuicocha as it lies in the present. This marked the beginning of a new phase of volcanic activity. This explosion ejected a significant amount of material and is widely considered to be one of the most powerful events in the Holocene of the entire Ecuadorian volcanic arc (M. Almeida, 2016; M. Almeida et al., 2023; R. Almeida & Rengel, 2020; Sierra et al., 2021). The pre-caldera domes around Laguna Cuicocha indicate that there has been recent volcanic activity, approximately 3,000 ya. Nowadays, there have been major changes, and they demonstrate that the Cotacachi stratovolcano was once connected to the Cuicocha collapse. The best-known tourist attraction in the area is Lake Cuicocha, a 2000 m wide caldera lake which receives almost 200.000 tourists per year as it has easy access and offers nice scenic views of nature landscapes. Wolf and Yerovi are two of the stunning islands that dot Caldera Lake. Compounded, these issues raise questions about the dangers of living next to a volcano (M. Almeida et al., 2023).

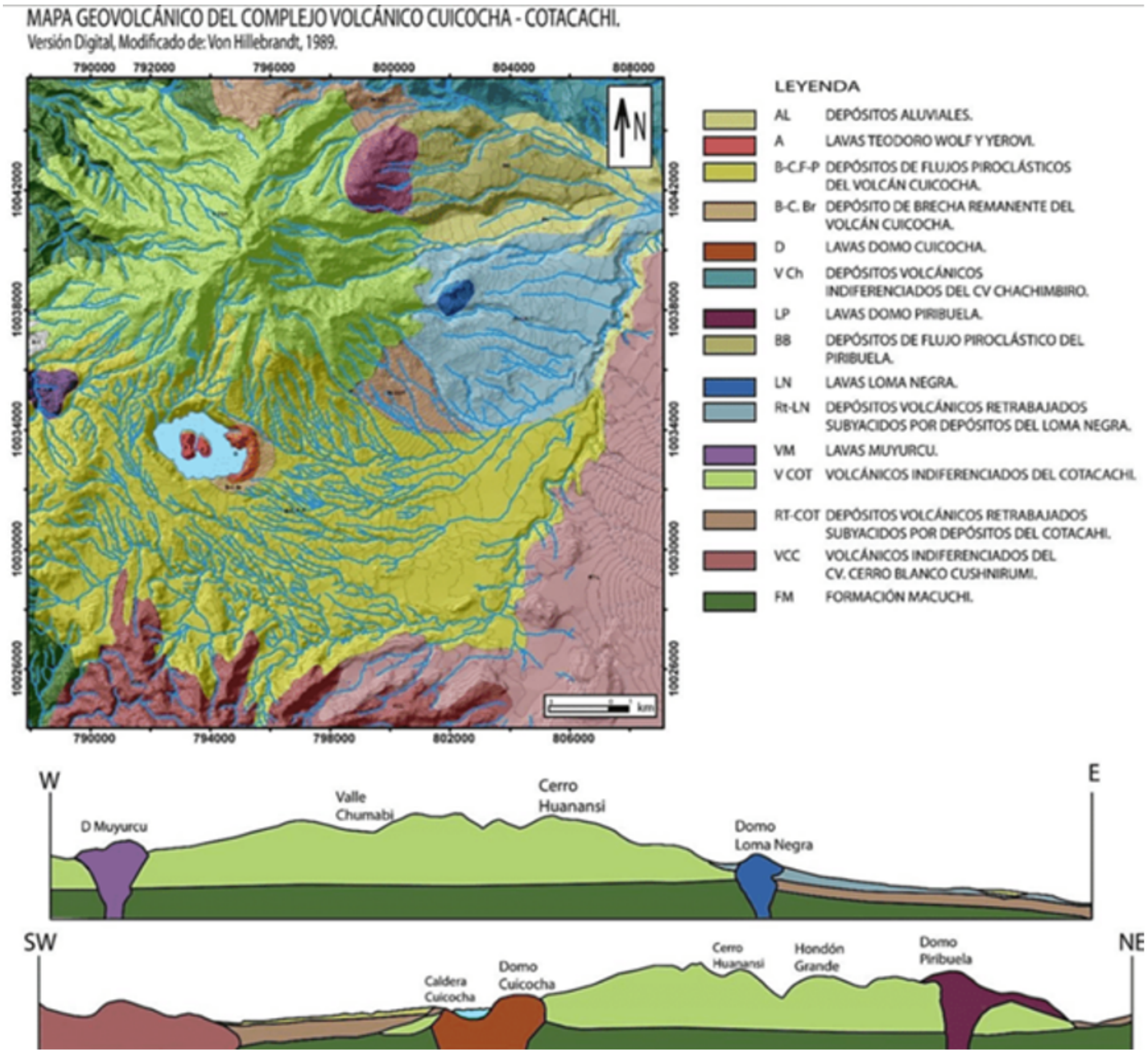


Figure 3.7: Digital Version, Geovolcanic Map Cuicocha-Cotacachi Volcanic Complex (Modified from: M. Almeida (2016))

### Representation of volcanic units

The Cotacachi - Cuicocha volcanic complex exhibits several key geological features that are essential to understanding its formation and evolution as is shown in Figure 3.8.

**1. Stratovolcano (Cotacachi):** Its formation occurred at some point between 173 $\pm$ 4 ka BP, late in the Pleistocene era. Named for its appearance, this stratovolcano is today one of the few areas that can be seen from miles around, geographically speaking.

**2. The peripheral dome:** which seems to piggyback directly on Muyurcu (138 $\pm$ 4 ka), Loma Negra (less than 108 ka), Piribuela (65 $\pm$ 2 ka), and the pre-caldera dome of

Cuicocha (about 3 ka), with different eruptive events from these bumps.

**3. Crater formation:** the volcano is now filled with water. Two post-caldera domes were made by an explosion that happened 2980 ± 30 a BP and made the current caldera. The crater and other features show that the area has been a volcano in the past.

**4. Chemical Composition:** The CCVC rocks are generally sodic to siliceous andesites and dacites, with silica concentrations ranging from 54.7 to 64.8 percent. This suite of rocks indicates that the calcium-alkaline, medium potassic magmatic type is prevalent in the Western Cordillera of the Ecuadorian Andes and the Inter-Andean Valley.

**5. Mineral Composition:** The geologic members of the CCVC have a distinctive mineral composition that varies with time. As the silica content increases, olivine gradually disappears and is replaced by amphibole and biotite.

The Cotacachi-Cuicocha volcanic complex: consists of a stratovolcano, outlying domes, crater development, diverse rock compositions, and unique mineral assemblages. These important geologic features provide insight into the geologic history of the complex and how volcanoes in the Ecuadorian Andes have changed over time. It was one of the analytical methods used to identify the volcanic units in the area (M. Almeida et al., 2023).

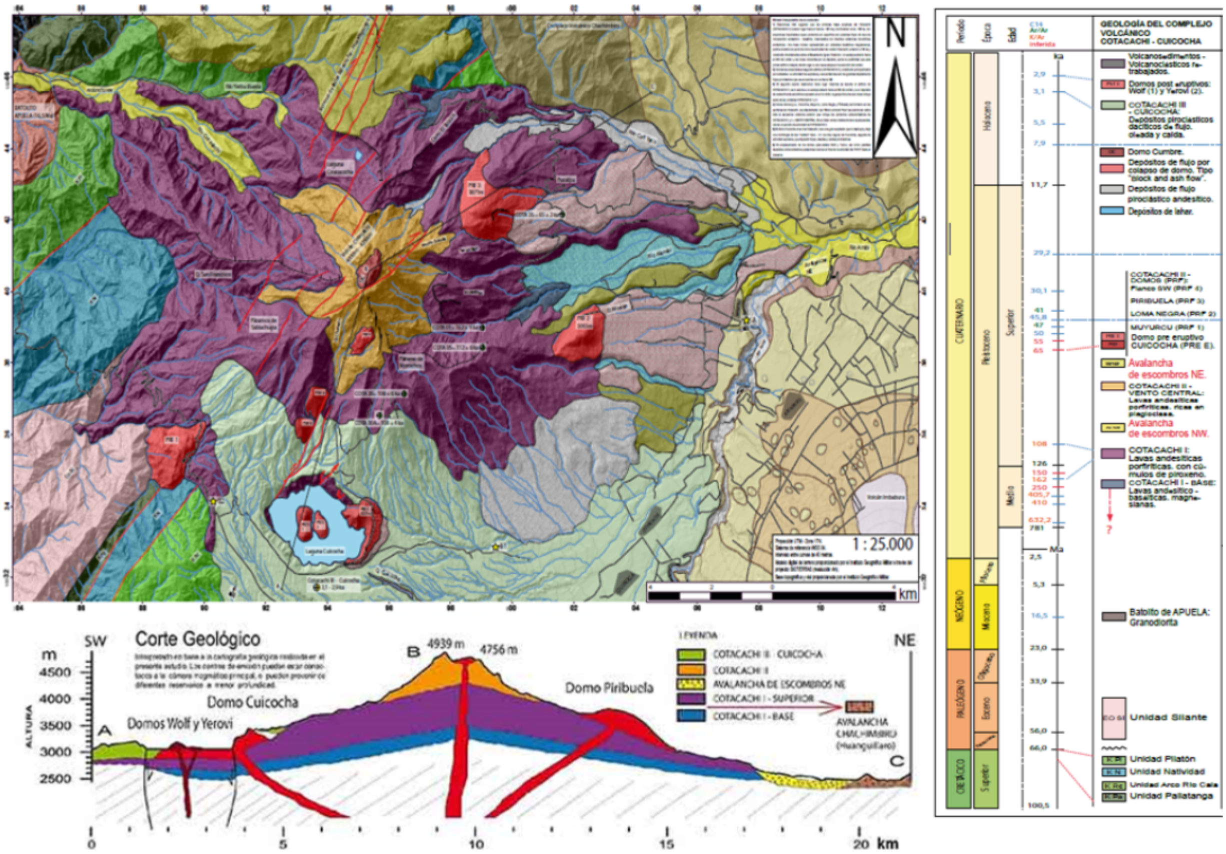


Figure 3.8: Geological Map of Cotacachi Volcanic Complex - CUICOCHA (Modified from: M. Almeida et al. (2023))

- · The CCVC is composed of three main layers: the Cotacachi Basal, Upper Cotacachi, and Cuicocha pre-caldera domes.
- · The Cotacachi Basal Member includes andesitic lava flows, basaltic-andesitic lavas, and peripheral domes such as Muyurcu and Loma Negra.
- · The Upper Cotacachi Member includes andesitic lava flows and debris avalanche deposits.
- · The Cuicocha pre-caldera domes indicate the onset of a new eruptive phase during the Holocene, which led to the formation of the Cuicocha Caldera Lake (R. Almeida & Rengel, 2020).

The authors conducted thorough 1:25,000 scale geologic mapping, which helped them locate and describe the various volcanic units in the CCVC. Lava flows, pyroclastic deposits, debris-avalanche deposits, and post-caldera mounds have been found in the area M. Almeida et al. (2023).

The geochemical data showed different amounts of some major and minor elements. The compositional analyses showed that pre-caldera domes were actually part of the Cuicocha Member, even though they appeared to be associated with the Cotacachi volcano. The authors combined chemical data with geologic maps and stratigraphy to recognize and describe the different volcanic units around the Cotacachi volcano-endothermal complex (M. Almeida, 2016).

### 3.2.2 Analysis of the Pichincha volcanic complex

The primary paper utilized to this section was developed by Robin et al. (2010). The Pichincha Volcanic Complex is in the Andes of Ecuador. A long history of eruptions began around 850 ka, during the middle Pleistocene. It is an important geological feature, with two tall volcanoes making up most of it: one that is not complete and one that erupted in the last 25 years. Guagua Pichincha, who is younger but has been active for a longer recent time. The older one is Rucu Pichincha. It is thought that Rucu Pichincha had volcanic activity between 850 and 150 ka. But Guagua Pichincha has been active for about 60,000 years. The biggest eruptions happened in the late 20th century and early 21st century, especially from 1999 to 2001 whose products are shown in Fig. 3.9. In terms of large scales of geographical time, the Pichincha complex is composed of the late Pleistocene and Holocene. The complex is unique in that it has numerous dacitic lava flows, an eruption of enormous power, and dome-shaped rocks. As a result of these activities, interesting geological panoramic features have been created and it is extremely dangerous. In the past, it has been surprisingly dangerous for the urban area of Quito, which is close to the volcano, every time it erupts. It is known that past eruptions have caused much volcanic ash and debris to fall on the people who live near the volcano, as well as their structures, leaving them ruined (Robin et al., 2010).


Figure 3.9: Geological setting of Guagua Pichincha volcano (Taken from: Colombier et al. (2022))

### Representation of Volcanic units

The Pichincha volcanic complex is comprised of numerous individual volcanic units, each exhibiting distinctive geological characteristics and compositions. The primary volcanic formations identified in the study include:

- **The El Cinto Unit** is composed of lavas of an estimated age of 1100 to 850 ka. The

El Cinto lavas are primarily andesitic to dacitic in composition and are distinguished by their relatively low potassium ($K_2O$) and incompatible trace element concentrations. It is hypothesized that these lavas are connected to the La Esperanza lavas, which are approximately 600 meters thick and located on the northern side of the volcanic complex. The geochemical characteristics suggest that these units represent the initial phase of volcanic activity that has subsequently been subjected to erosion and partial burial Robin et al. (2010).

- **The Rucu Pichincha Unit** is characterized by the presence of andesitic to dacitic materials, related with low levels of potassium ($K_2O$) and other trace elements. It is thought that these lavas are connected to the La Esperanza lavas, which are around 600 m thick Ego, Sébrier, Lavenu, Yepes, and Egues (1996). Rucu Pichincha is a stratovolcano that has undergone three distinct phases of construction. The majority of the rocks in this unit are andesitic, exhibiting a silica ($SiO_2$) concentration that varies between 59 and 63 percent. The mineral composition is comprised of plagioclase, ortho- and clinopyroxene, Fe-Ti oxides, and a minor proportion of amphibole. The evolution of Rucu Pichincha has been marked by significant instances of collapse, which have shaped its current configuration Legrand et al. (2002).

- **The Guagua Pichincha Unit (GGP)** represents the section of the Pichincha complex that has experienced volcanic eruptions over the past 60 ky. The most notable attribute of the GGP is its extensive range of magmatic compositions, with $SiO_2$ concentrations spanning from 58 to 66 percent (Barberi et al., 1992). The volcanic history is characterized by long periods of dome formation and explosive eruptions, which have had a considerable impact on the formation of the current volcanic structure. The Guagua Pichincha volcano has experienced notable collapses, particularly during the transition from the Pleistocene to the Holocene period. Consequently, an amphitheater has been formed, which is currently utilized by the operational Cristal dome (Robin, Samaniego, Pennec, Mothes, & van der Plicht, 2008).

- **The Toaza Unit** is a minor formation that emerged subsequent to a significant portion of Guagua Pichincha collapsing approximately 4,000 ka. The Toaza unit is notable for its relatively modest dimensions and its distinctive history of eruptions, which has contributed to the overall complexity of the Pichincha volcanic complex (Samaniego, Robin, Chazot, Bourdon, & Cotten, 2010).

- **The Cristal Dome** is a recently formed volcanic structure within the Pichincha complex, the formation of which is the result of ongoing volcanic activity. This volcano represents the last stage of volcanic explosions. At present, the volcano is considered active, and it represents a potential hazard to the neighboring urban areas, most notably the city of Quito (Robin et al., 2010).

### 3.2.3 Analysis of the Imbabura volcano

For the purpose of conducting an analysis of the Imbabura volcano, the paper written by (Andrade et al., 2019) was taken into consideration. The Imbabura volcano, situated in the Ecuadorian Andes approximately 60 km north of Quito, is a prominent stratovolcano that has undergone significant geological transformations over the Quaternary period, particularly from the late Pleistocene to the early Holocene (Fig. 3.10). The initial volcanic activity, which is associated with the ancient structure designated as Imbabura I, is estimated to have occurred approximately 30 ka, placing it within the late Pleistocene era. During the first stage, there was a large volcanic collapse that moved material in a direction between N330 and N340, changing the landscape. After this event, three more buildings were former, named Imbabura II-1, II-2 and II-3. Imbabura II-1 was formed around 20 ka and remained in place during the Holocene (Fig. 3.12 (Alvarado et al., 2014). In the more recent units, different eruption types are included, such as lava flows and domes and explosive eruptions. The structure of Imbabura is complicated. Different volcanic blocks show petrographic and geochemical features that are unique to each block. These features indicate that the extrusion came from different source areas and also underwent different types of processes over time. Finally, the activity of the Imbabura volcano has had an effect on the structure of the underlying rock, while the nearby Cubilche volcano causes the underlying rock to dip to the north (Fig. 3.11) Andrade et al. (2019).

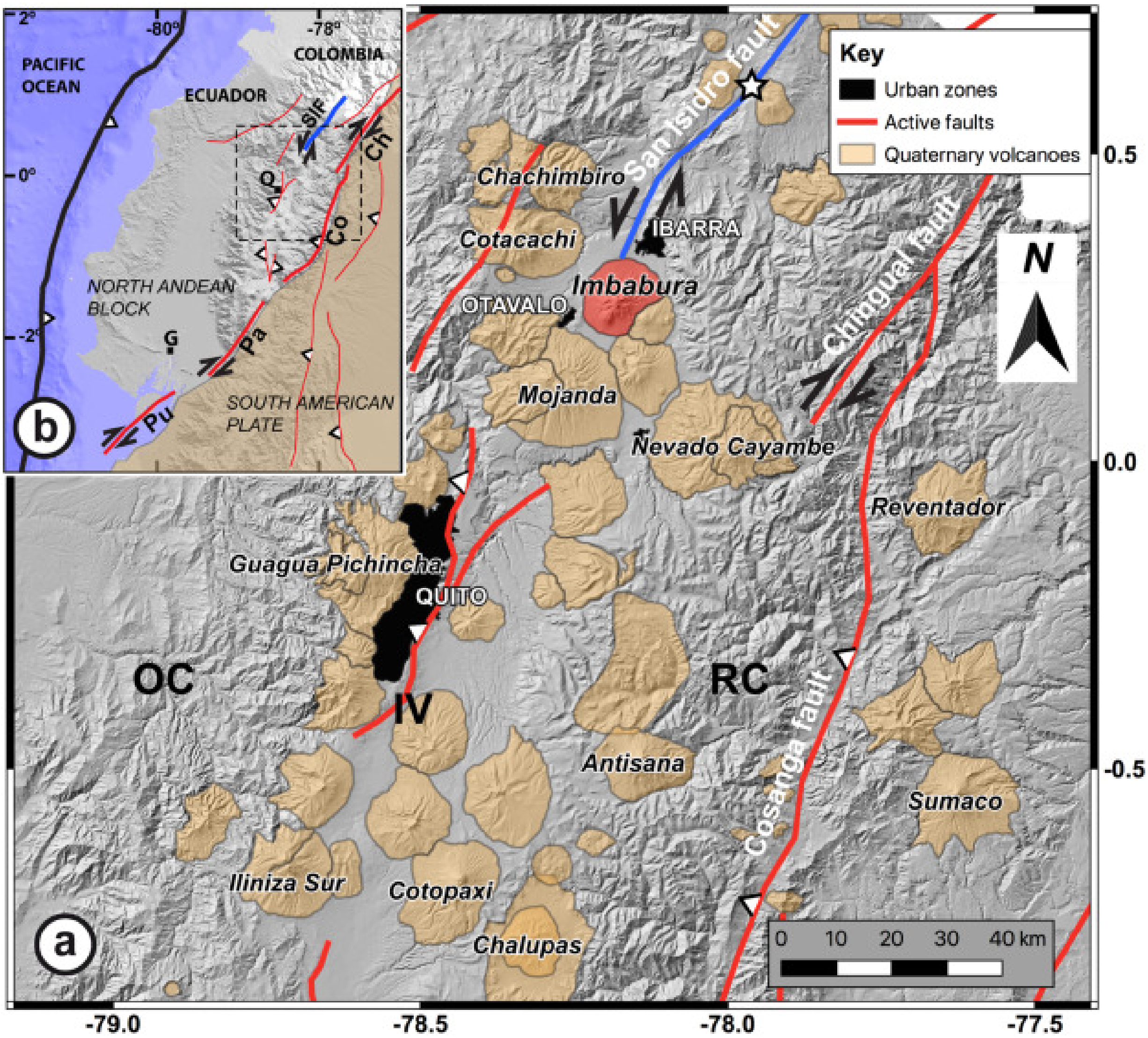


Figure 3.10: Map of the northern Andes of Ecuador, showing the Quaternary volcanoes (Taken from: Andrade et al. (2019))

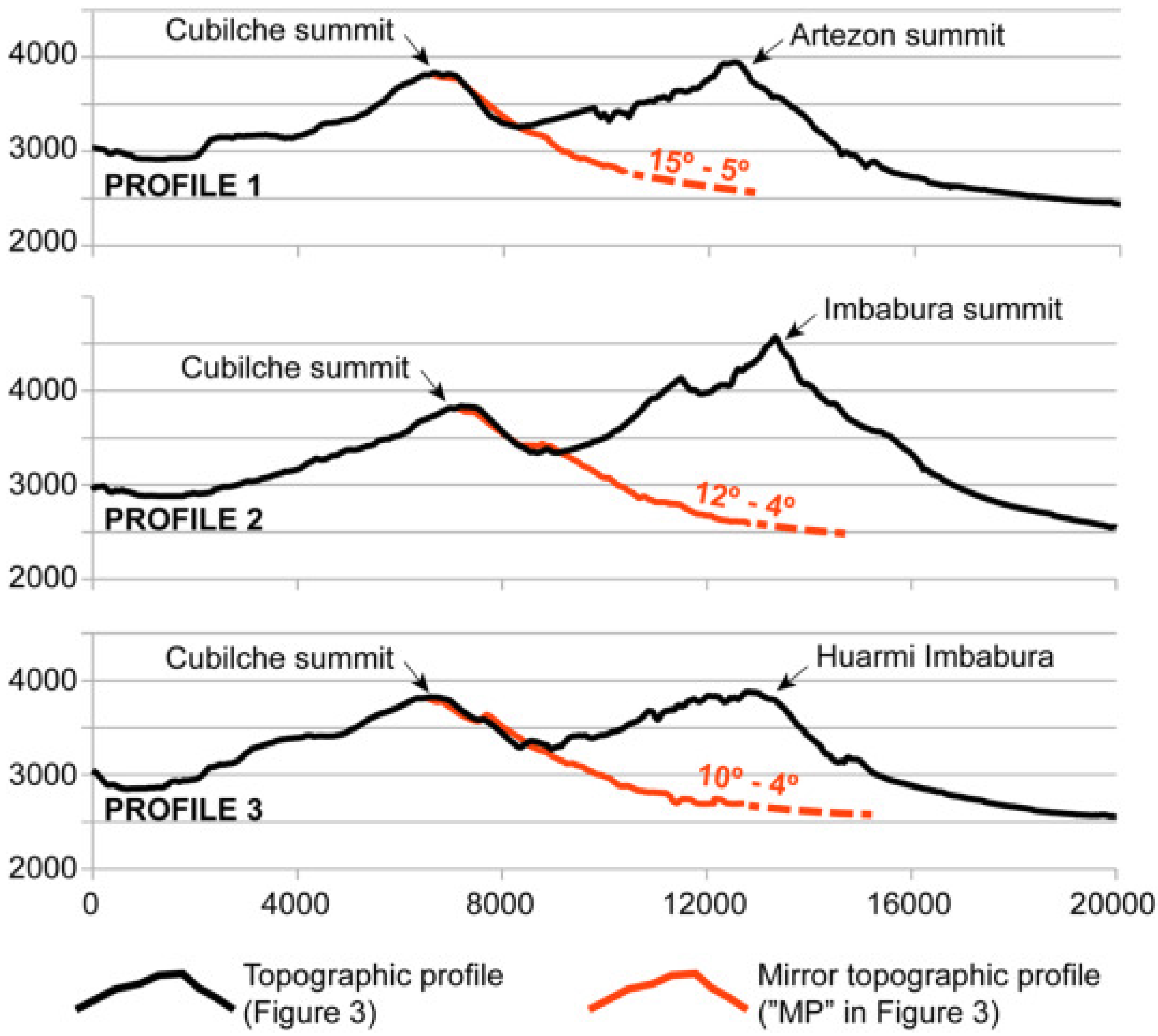


Figure 3.11: Topographic profiles across Cubilche and Imbabura edifices (Taken from: Andrade et al. (2019))

### Representation of Volcanic units

Researchers at Imbabura volcano study the way some of the volcanic rocks are grouped. To define different units, it is important to consider factors such as the rocks they contain, the size of the crystals, and their chemical composition. Researchers also look at whether different parts of the volcanic complex make up its spatial arrangement and how old they are chronologically (Acuña, 2021). Petrographic and geochemical studies of the Imbabura volcano have yielded important discoveries Andrade et al. (2019).

- **I.** In this classification method, the different volcanic units are identified: According to studies of petrography and geochemistry, there are separate volcanic units known as Imbabura I, Imbabura II-1, II-2, and II-3. These units present different mineral structures. Suggesting that each of these units may have originated in a different location and undergone a different growth process (Lagmay, van Wyk De Vries, Kerle, & Pyle, 2000).

- **II.** These are the stratigraphic relationships. The study showed how the different volcanic units are stratigraphically related. It also showed the sequence in which lava flows, secondary volcanic rocks, and avalanche units formed Group II. Radiometric dating has made it possible to place precise time limits on the formation of these elements (Egüez, Alvarado, Yepes, Machette, & Dart, 2003).

- **III.** How the overall structure has evolved over time: To understand how Imbabura has evolved over time, a study of the genesis and movement patterns of the volcano's structure was undertaken. The results showed that the growth of the volcano and the layer beneath it were intricately linked. These connections greatly influenced where the volcanic structures were placed and what they were made of (Pennec et al., 2011).

- **IV.** The evolution of geochemistry: It could be seen that the elemental composition, such as $SiO_2$, Sr, Ni or Mg, varies for separate volcanic rocks. This indicates that the magma and the sources of the volcano have changed over time (Hidalgo et al., 2007).

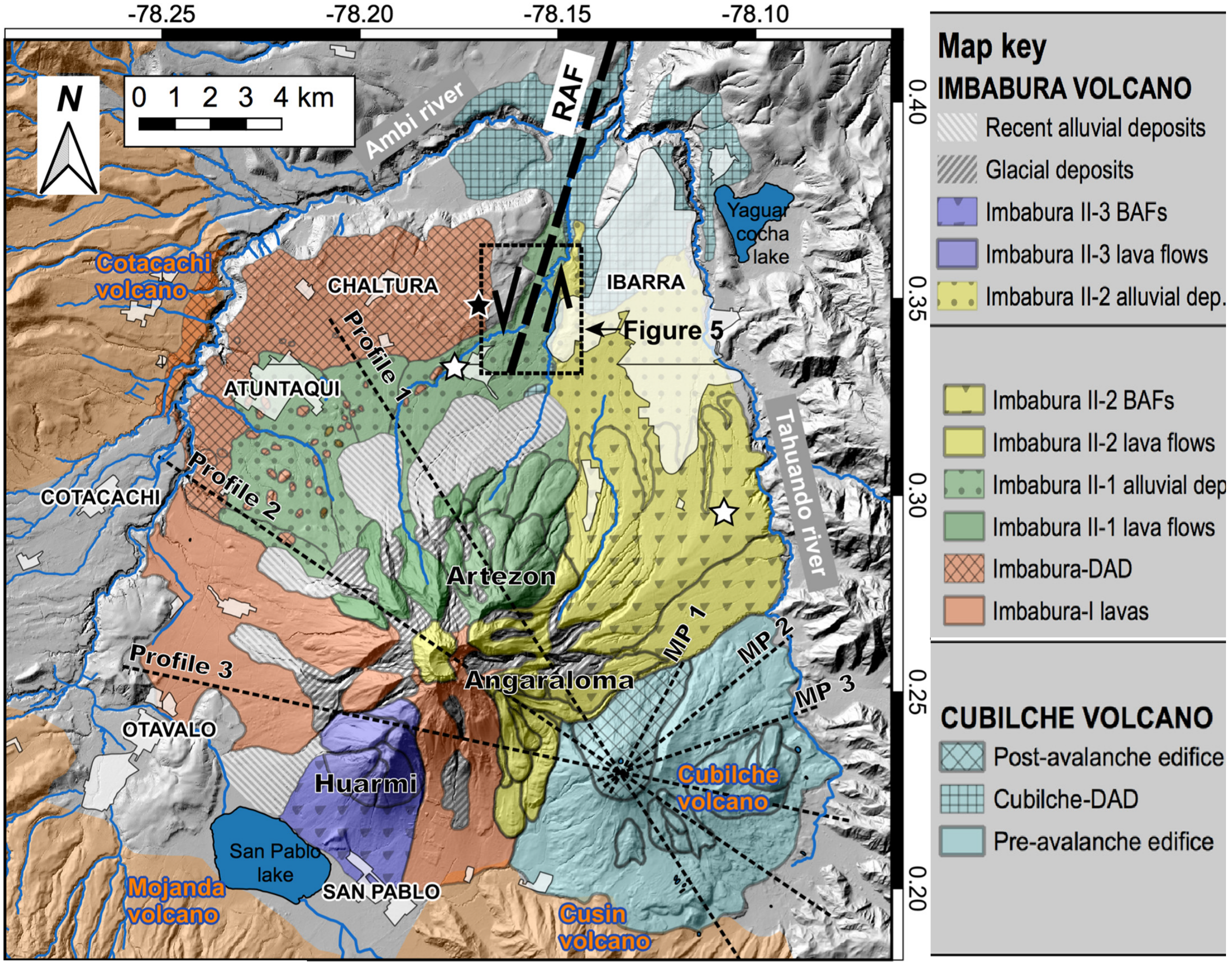


Figure 3.12: Geological map of Imbabura (Modified from: Andrade et al. (2019))

### 3.2.4 Analysis of the Antisana volcano

This part of the research is mainly related with the paper of Hall et al. (2017). Antisana volcano in the Eastern Cordillera of Ecuador (Fig. 3.13) is a large andesitic stratovolcano that was most active during the Pleistocene, from about 2.6 Ma to 11,700 ya. A very complicated natural history characterizes this volcano. This includes the formation and destruction of two predecessor volcanoes, named Antisana I and II, during more than 400 ka. Antisana I is a small, highly degraded cone of basic andesitic rock. Antisana II's sister Important erupted at the same time and grew to be the largest building before partially collapsing around 15 ka (Fig. 3.14. More than 50 eruptions of moderate to low magnitude have been recorded at Antisana. Andesitic explosions typically have a consistent pattern at this volcano. In return, andesitic to dacitic lava flows were produced, and tephra layers were often released in connection with these events. Throughout the Holocene epoch, which began about 11,700 ya and continues to the present day, there has been a change to dacitic materials. In its lavas, we can see the unique natural characteristics of the Antisana volcanism. For a long time, several mixed minerals have been found, such as plagioclase, clinopyroxene, orthopyroxene, and Fe-Ti oxides, which are geographically close to each other and represent the common transition to dacitic materials. Occasionally, dacitic materials can also occur in lavas, such as those at Antisana, located within the Northern Volcanic Zone of the Andes; this paradigm of andesitic magmatism vividly reflects the complex interplay between tectonic and magmatic processes (Hall et al., 2017).

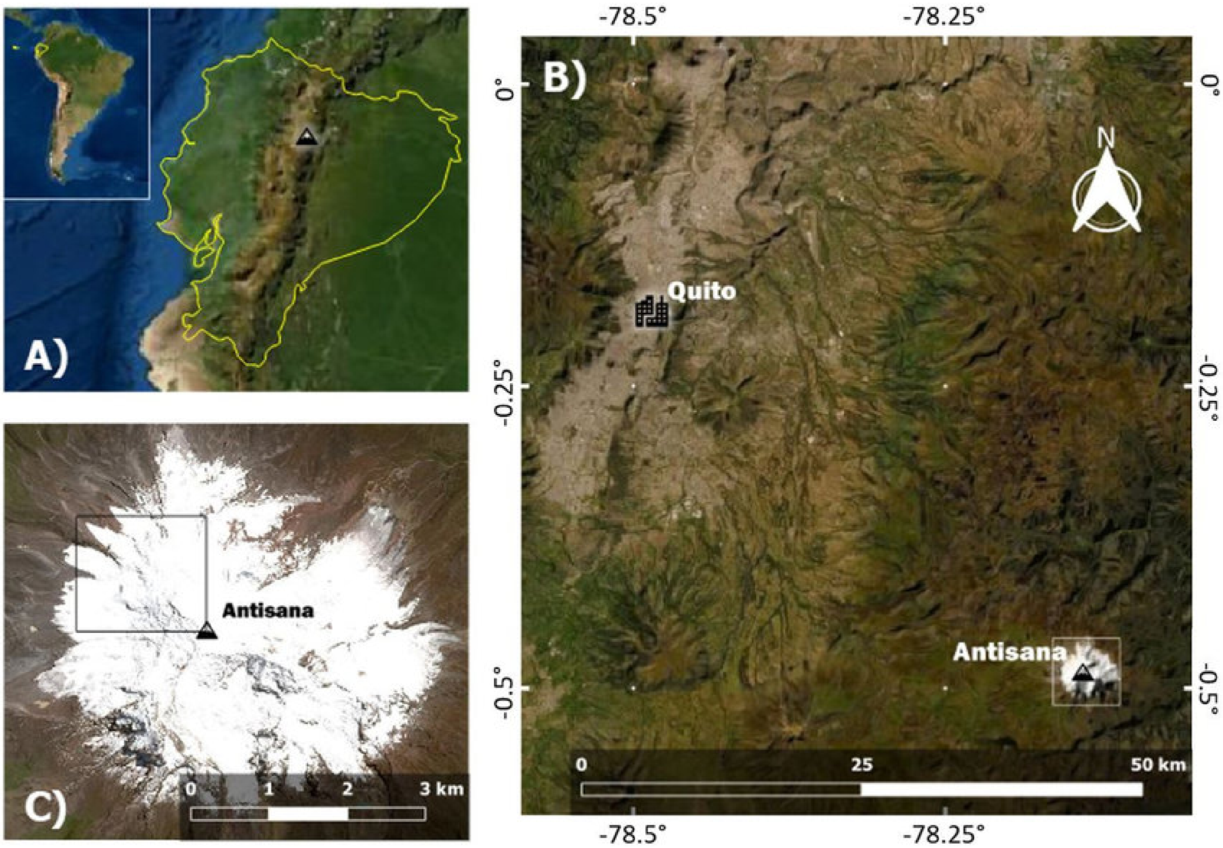


Figure 3.13: Location of the Antisana volcano, in the Napo province of Ecuador. (Taken from: Cabrera et al. (2020))

The methodology used to study the Antisana volcano began with reconnaissance and petrographic studies around the volcano starting in 1996. The expedition involved the collection of geological samples and data, which were then subjected to extensive analysis using petrographic techniques and stratigraphic methods. Radiocarbon dating was used to determine the timing of the volcanic events and the glacial advance associated with these eruptions. Researchers also conducted chemical studies to learn more about the formation and growth of volcanic products, focusing on the groups of lava minerals that are so common in lavas. Furthermore, the researchers looked back at information from studies done by Humbolt, Wolf and other recognized international experts. This multifaceted approach allowed for a close look at the natural history of the land, how it erupted, and how its chemistry evolved. This helped scientists to understand its importance to the Andes today, the northern part of the study of the central volcanic zone of the Andes today (Hall et al., 2017). In their study, the authors define the volcanic units around Antisana through an analysis of the stratigraphy, petrography, and geochemistry of the deposits. Identifying, characterizing the volcanic units based on their lithological, textural, compositional and chronological features. The volcanic units are grouped in categories, including andesitic scoria and lapilli layers, pumice tephra beds, lava flow units, lahar and glacial-fluvial units, pyroclastic flow deposits, distal ash beds, and varve layers (Hall et al., 2017).

### Representation of Volcanic Units

For the past 400 ka, Antisana has grown by building and then destroying two older structures, which are known as Antisana I and II. This was followed by the rise of Antisana III and its growth. A sector failure happened in Antisana II about 15 ka ago, which caused Antisana III to appear. Antisana III has been busy, with more than 50 outbursts of moderate to large size. These have made tephra and lava flows that are andesitic to dacitic. Also, the earthquakes of Antisana III have been linked to the movement of ice from the late Pleistocene and early Holocene times. Antisana's lavas have always had the same material makeup. They are mostly made up of phenocrysts of plagioclase, clinopyroxene, and Fe-Ti oxides, with olivine or amphibole showing up every once in a while (Hall et al., 2017). The Antisana I and Antisana II structures are older than the Antisana III volcano.

**Antisana I**

It is the oldest of the buildings, and its volume is believed to be about 5.4 $km^3$. There is a lot of hydrothermal alteration inside the building, which shows how old it is and how the geology of the area has changed over time.

**Antisana II**

The Antisana II building is at the central peak or just to the north of it. Since the lava flows on the N, E, and S sides of the current Antisana mountain slope away from the central peak ridge, it is thought that these sides are leftovers of Antisana II.

**Antisana II**

It is believed to have been about 33 $km^3$ in size and would have been around for more than 400 ka. Soon after Antisana II was formed, a sector falls of about 0.5 to 1 $km^3$ volume happened. This made a big valley that goes all the way to the current Antisana summit. After that, there was a fall that made Antisana III the volcano's youngest vent and current peak. The current peak of the Antisana volcano is Antisana III, which is the smallest vent. It is on the western side of the Antisana II building, which has been damaged by weathering. Antisana III's top is shaped like a flattened cone. This is likely because glaciers filled in its crater. In the Late Pleistocene and Holocene periods, all lava flows began at this peak and mostly went north, west, and southwest. Young lava flows that go under the western and northern glaciers and reach the top prove that the summit cone is where the current emissions are coming from. Around the base of the west of the building, a large volcano-clastic apron has formed. It is made up of thick layers of tephra, lavas, pyroclastic flow units, debris flow deposits, and other debris (Hall et al., 2017).

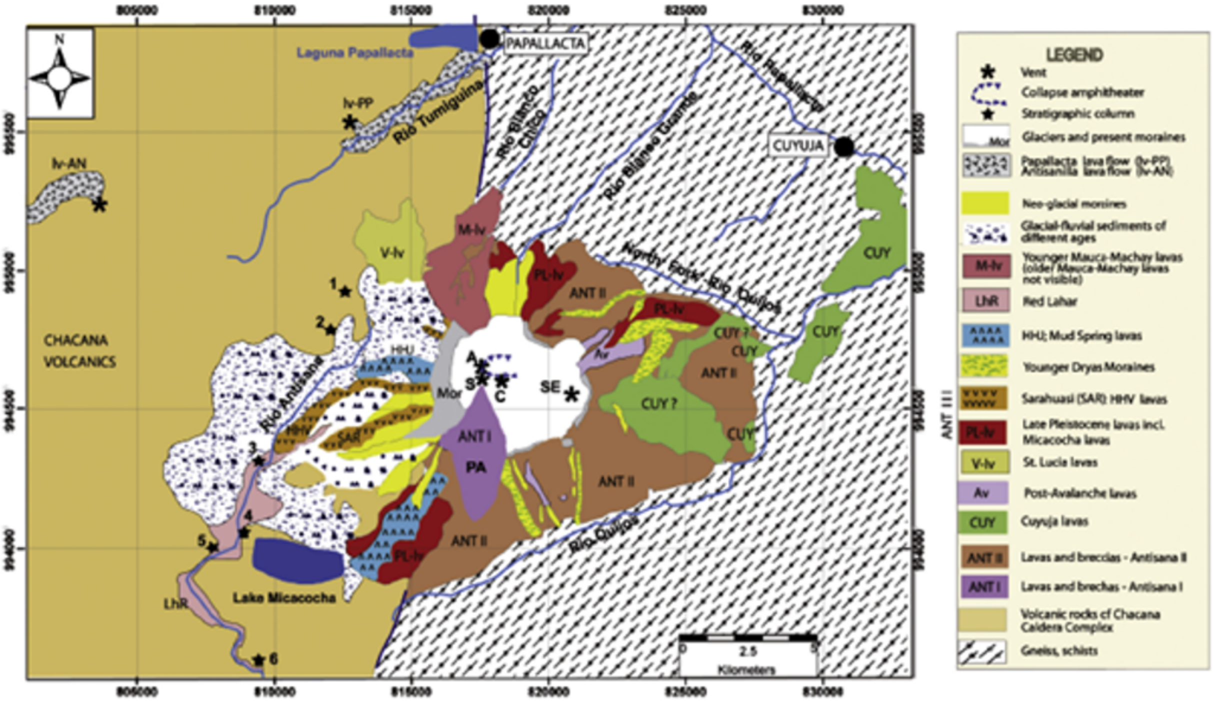


Figure 3.14: Geologic sketch map of Antisana volcano and surrounding areas (Taken from: Hall et al. (2017))

## 3.3 General definitions for classifying lithostratigraphic units

### 3.3.1 The International Stratigraphic Classification

The stratigraphic classification, as established by Murphy and Salvador (1999) in accordance with the rules set forth by the *International Commission on Stratigraphy* (ICS) and the *International Union of Geological Sciences* (IUGS), categorizes formal stratigraphic units based on their distinctive traits and characteristics. The following units are included:

- 1. **Lithostratigraphic units,** are defined by the lithologic characteristics of the rock beds. This provides the viewer with information about the composition of the rock and how it is structured.

- 2. **Chronostratigraphic units,** in order to create chronostratigraphic units mainly is related to find out how old the rock forms are. Then geological events can be easily placed in time.

- 3. **Different biostratigraphic** zones are distinguished according to the types of fossils found in rock layers.
- 4. **Discontinuity bounded units,** These units are made up of solid blocks of rock that are separated above and below everywhere by large gaps in the succeeding rock layers. These gaps in the rock record important natural events and form boundaries.
- 5. **Magnetostratigraphic Polarity Units,** are derived by observing how the orientation of residual magnetism in rock layers can change over time. This technique therefore gives us a clue as to how the Earth's magnetism behaved in the past.

### 3.3.2 Volcano

As defined in the *"Glossary of Geology"* (1997, p. 690), a volcano is an opening in the Earth's surface that enables the release of magma, gases, and ash during eruptions. Additionally, it can signify the conical form or configuration resulting from the ejection of materials. To encompass a multidisciplinary perspective on volcanoes, definitions must be revised to incorporate essential characteristics pertinent to numerous disciplines. For instance, they tend to prioritize either volcanic activity or their physical structure Borgia et al. (2010). Published in 2010, the book *"What is a Volcano?"* Borgia et al. provides a thorough and wide analysis of the existing definition of a volcano. The discussion highlights the observation that volcanism exhibits self-similarity on several levels, encompassing spatial and temporal dimensions. Several geological processes, such as magma formation and differentiation, tectonic activity, erosion and sedimentation, volcanic eruptions and intrusions, and hydrothermal systems, have an impact on this process. A volcano is defined as a geological setting consisting of three main components: magma, eruption, and building. Confirmation of any one of these factors is sufficient as long as the presence, past existence, or future possibility of the others can be inferred. In general, a volcano is a complex igneous system that forms on the Earth's surface. It includes everything from the subsurface magma source to the apparent vents and craters on the surface, as well as the volcano itself and any associated intrusions. The concept focusing on the eruptive subsystem is derived from Szakács (2010), who defines the volcano as the uppermost segment of a volcanic system. In the past, the definition of a volcano included only the pathway connecting the underground magma chamber to the surface, such as the chimney and the crater. It did not include the entire system of molten rock below the surface. The results of the volcanic definition survey indicate that there is an imperative need for a more comprehensive approach that includes a variety of geologic features. Traditional definitions, such as those found in the Glossary of Geology (1997), tend to focus exclusively on specific features, such as the surface vent or the resulting conical structure, and often overlook the broader volcanic system. In addition, the integrative technique proposed by Borgia et al. (2010) emphasizes the importance of considering the interrelatedness of magma, eruption, and edifice, which together form the entire volcanic organism. According to Szakács (2010), a volcano is included as a component of a broader volcanic system that also includes subterranean components. This view is consistent with this concept. By expanding the definition to include these components, it is possible to recognize the complex interactions and processes that are responsible for defining volcanic activity. Therefore, a volcano should be defined by including its many aspects and geologic processes. A volcano is more than a conical eruptive structure or a surface vent for magma, gases, and ash. It is a complex igneous system formed and evolved by magma, eruption, and building. A volcano is a geologic setting defined by three elements: magma, eruption, and edifice, regardless of its size. It is sufficient to establish the existence of any one of these variables as long as the others can be assumed to exist, to have been present, or to have the propensity to be present in the future (Borgia et al., 2010). In this study, a volcano is defined as a complex geological system that encompasses the entire igneous framework, from the subsurface magma source to the visible vents and craters on the surface. This approach is consistent with the comprehensive definition proposed by Borgia et al. (2010), which recognizes a volcano as a complex geological system that encompasses the entire igneous framework, from the subsurface magma source to the visible vents and craters on the surface. This encompasses the broader volcanic system and any associated intrusions. The representation of volcanic units varies in detail, depending on the specific focus of the study. In this study, a volcano is defined as a geologic setting characterized by three main elements: magma, eruption, and edifice. It is sufficient to establish the existence of any one of these components, as long as the presence, past existence, or future possibility of the others can be inferred (Szakács, 2010).

### 3.3.3 Lithosome

A lithosome is a general geological unit used to describe any given section of a volcanic area, such as for example Etna. Lithosomes have different physical appearances while outcropping around volcanic hills. The names of the units were based on localities within an area to reflect and give concrete expression to how widely scattered, we might add widespread, are the shapes and sizes of vent-ridges scattered throughout a volcanic complex (Battaglini et al., 2009). It is in this way that we can see how eruptive centers are spread out in space and how they are built into the volcanic complex as a whole. Broadening the definition of a lithosome to encompass better the intricate and interrelated geological processes involved in the subsurface processes and interactions between volcanic centers will greatly improve the ability to characterize and standardize these stratigraphic volcanic units (Branca et al., 2011).

### 3.3.4 Supersyntheme

Supersynthemic units can be categorized according to the four stages of development proposed for Etna by Branca et al. (2004), an even higher level of grouping for lithostratigraphic groups or synthems. Such supersynthems serve to organize or sort volcanic units into larger units that may represent important stages or events in Etna's past. One can observe what kind of volcano it is by its shape and structure in the field. This method of observation makes it easier to determine how volcanic activity has spread across the mountain. Intensive fieldwork and meticulous stratigraphic sectioning were required to position lithostratigraphic units within the sequence accurately and to consolidate their relationships. In the field, it was also very important to identify and collect statistics on these units. Hence, the name Branca et al. (2011) By using a supersynthemic classification, it's possible to classify lithostratigraphic groups in a more complex and thorough manner. Using a hierarchical approach makes the many steps in the formation of a volcano easier to understand because all volcanic units are placed into categories. Methodical data collection in the field is required to identify these kinds of units and record the rock layers. Ensuring that the information collected is accurate and reliable. This is the foundation of a good classification system. By incorporating the supersyntheme into the proposed volcano-stratigraphic framework, it is feasible to make rational classification of volcanic deposits.

### 3.3.5 Syntheme

The "synthem" represents a lithostratigraphic unit modified with respect to its boundaries by unconformity surfaces in the volcanic series. The unique term for this rank is the "unconformity-bounded unit" (UBU), as it arises where large numbers or thick volumes of lava manage to force eruption. The concept of synthemic units provides an understanding of the spatial organization of rock formations linked to the major stages of Etna volcano's geological evolution, as identified by unconformity boundaries. Erosion and unconformities define the limits of each synthem; hence, they can be correlated with a distinct geological unit in another part of the volcanic sequence. The amalgamation of field data, lithostratigraphic criteria, and geochronometric dating helps to define the synthem boundaries precisely. This scheme allows us to order and make sense of Etna's complex volcanic history. With respect to the geologic mapping of Etna, lithostratigraphic units are referred upon synthems as UBUs that match in a fulfillment rationalized set by unconformity surfaces (Branca et al., 2008). These remarks will show in great detail spatial large-scale stacking of rock types and their genetic history, documenting the strong episodes of Etna's growth through eons. Further applications would include wide applications for general studies of earthquake stratigraphy. The combination of field data, lithostratigraphic criteria, and radioisotope dating allows a precise definition of synthem boundaries. Consequently, it provides us a holistic view to comprehend the complex historical aspect of volcanoes, giving more precise geological information and thus leading to rational decisions in terms of volcanic or management.

## 3.4 Analysis of Collected Data

The research builds on the findings of a number of previous studies, resulting in a picture that illustrates the complexity that exists within volcanic geology. It shows that the categorizations lie on a spectrum, with some very simple and others much more complex. We use each level of classification for different things, from our region-wide assessments to detailed neighborhood studies. They are essential to understanding the diverse and complex workings of volcanoes. In the following sections, I will provide a comprehensive analysis of these groups. This will be accompanied by a detailed description of how and why they are used in scientific studies. Volcanic areas have a complex geologic past based on stratigraphic units that range in size from supergroups to individual flow units. These methods allow geologists to assess the various phases of volcanic events in a structured manner, beginning with magma emplacement, followed by the formation of eruptive edifices before final accumulation in porous materials. This systematic approach does more than allow us to understand volcanic eruptions better or provide a tool for improved geological mapping of ancient and buried volcanoes. By breaking down volcanic layers into individual units, scientists can better understand the time scale of eruptions. This allows them to correlate an event at one site with a distant impact and provides insight into how the volcanic surface has evolved over time.

### 3.4.1 Level 1: Supergroup

The initial stage of volcanic stratigraphy employs a range of linguistic tools and techniques to define and categorize volcanic deposits. This includes terms such as ”supersystem,” ”volcanic complex unit,” and ”lithostratigraphic unit.” A supersyntheme is defined as a significant stratigraphic unit comprising two or more systems. This approach allows for a comprehensive study of the history of an entire volcanic system, as demonstrated by Branca et al. (2011) and (Martí et al., 2018). Similarly, a volcanic complex unit is a specific examination of deposits related to a particular volcanic complex. Finally, a lithostratigraphic unit is a classification of groups that have similar geological properties, which makes it easier to map volcanic systems at a local scale and conduct regional investigations.

#### Supersyntheme

A major division of volcanic stratigraphy that groups two or more synthems with distinguishing geological features and enables us to understand the evolution of a whole volcanic system is called a supersyntheme or lithostratigraphic group (Branca et al., 2011). The identification of the Main Lithostratigraphic Units in the La Garrotxa volcanic field is noted in the research of Martí et al. (2018), where several volcanic formations with particular features are differentiated. These units may also be referred to as ”lithosome units” or ”volcanic complex units” in another research, such as Branca et al. (2011) on the Valle del Bove volcanic complex at Etna.

#### Lithostratigraphic Unit

A lithostratigraphic unit consists of two or more groups that do not have important genetic relationships. This is particularly convenient since it facilitates the association of similar volcanic systems for small-scale mapping as well as regional stratigraphy. Every unit within the group retains its characteristics while at the same time extending our knowledge of a region’s natural history. It also speaks to the importance of clearly defined lithostratigraphic units when studying volcanic systems. The survey examined, such as that of Branca et al. (2011) and (Martí et al., 2018)

### 3.4.2 Level 2: Group

At this level of volcanic stratigraphy, ”synthemic units” and ”lithosome units” are closely related and play an active role in classification. Synthemic units represent important steps in the growth of a volcano and can now be described as a stratigraphic and a volcanic criterion. With certain unconformity planes (Branca et al., 2004), all lithologic variation has been interrupted. Lithosome units are used to group rocks with similar petrological characteristics (Branca et al., 2008). First, it allows us to interpret the geologic data in regional studies. Second, the classifications allow for control and comparison of volcanic activity and the formation of volcanic systems (Albán, 2019).

#### Group/Synthemic Unit

In the field of geological study of volcanic systems, a synthem is a concept that combines stratigraphy and volcanic factors to give us an overall picture of the past life and present situation of a volcano. This method divides the rock layers that show a volcano’s geologic history into groups by finding the unconformities in volcanic successions. Each synthem in the stratigraphy is a different unit in the volcanic sequence, with time gaps between them caused by erosion and unconformities. Branca et al. (2004) suggest that the boundary between synthems is delineated by methods such as radioisotope dating and litho-stratigraphic standards, as well as field observations. Building on this idea, synthemic units also allow us to show how important individual explosions are as basic building blocks. In this way, the stratigraphic record left by volcanic action is clearly related to how volcanoes in turn erupted material that can be used as a template for historical reconstruction. Used in conjunction with other methods, synthemic units provide a solid basis for studying and understanding how complex volcanic systems form and change over time.

#### Lithosome Unit

Lithosome Units is a division of the volcanic stratigraphy that groups deposits with comparable lithological properties. Lithosome Units are used in the study of Branca et al. (2011) on the Valle del Bove volcanic complex at Etna to characterize several groups of volcanic deposits with comparable compositions. A unit that ranks immediately above a formation is referred to as a group in the context of lithostratigraphic classification. Usually, two or more contiguous or related formations that share important and diagnostic characteristics are included in this type of group. These associations are especially helpful for interpreting geological data on regional stratigraphic studies and small-scale maps (larger than 1:100,000). The usefulness of a formation in streamlining the categorization for certain geographic areas or stratigraphic intervals should determine whether or not to include it in a group. It is crucial to remember that determining whether a group of formations is comprised of a set of formations should not be determined by the thickness of the stratigraphic succession. Moreover, it is not necessary for group formations to remain consistent from one place to another. (Albán, 2019).

### 3.4.3 Level 3: Formation

Formation: A collection of volcanic deposits that are distinguished from neighboring formations by unique lithological characteristics or a specific level of lithological uniformity. In volcanic stratigraphy, these formations are regarded as mappable units, and they have to be representable cartographically at the size of the maps that are in use in a particular area. Volcanic structures can vary in thickness from a few millimeters to several thousand meters (Murphy & Salvador, 1999).

According to the categorization system used in lithostratigraphy, a Formation is the main formal unit. It can be distinguished from nearby formations by its unique lithological characteristics or by the degree of lithological uniformity it exhibits. The only formal lithostratigraphic units where the stratigraphic column has to be completely classified according to lithology whenever it is seen are formations. A Formation can only be justified or made practical if it can be demarcated at the appropriate map size. A Formation can only be effective if it can be mapped at the scale employed in the particular region of study. These formations vary greatly in thickness, from less than a meter to several thousand meters (Murphy & Salvador, 1999).

In this way, Volcanic Formation is used in the Madeira volcanic field in the research of Marti, Mitjavila, ', and Aparicio (1992), where several stratigraphic units that make up the island's eruptive history are recognized. Terms like "Volcanic Activity Units" or "Individual Eruptive Units" are used to characterize distinct groupings of deposits in various situations, such as charting volcanic regions on Mt. Etna. These units offer a comprehensive and methodical approach to recording and comprehending a region's volcanic past; every formation may be identified and mapped at the proper size (Martí et al., 2018).

### 3.4.4 Level 4: Member

In lithostratigraphy, a member is always part of at least one formation and lies directly below formations. In a structure, each part belongs to different parts and is given a specific name according to its characteristics, which distinguishes it from relative members. There may be some formations in which there are only a few members, and there may be no members at all in the formation. This provides descriptions of the members so that you can identify groups in a more diverse creation. However you formally categorize a person, there is no need to map it at the same scale as the organization. Bodies of rock that differ in lithology from the unit around them are called lenses and tongues if they have prominent connected dimensions (centimeters to meters long). A tongue is a thinner extension of the body of a lithostratigraphic unit (Murphy & Salvador, 1999).

In the study by Marti et al. (1992) on the Las Cañadas crater system in Tenerife, eruptive members were found for each individual eruption that contributed to the formation of this volcanic complex. Similarly, introduced the concept of ”eruptive pulse units” based on geological and volcanological criteria to subdivide discrete eruptive events. Whether the formation is official or not, an eruptive member does not have to adhere at this size anywhere in the section. We can learn more about geology and volcanic history by using this method to identify specific eruptive events within an entire volcanic system.

### 3.4.5 Level 5: Bed

The smallest formal unit in sedimentary lithostratigraphy is ”bed.” It describes a single stratum that may be distinguished from the strata immediately above and below it uses lithology. Beds clearly provide benefits in stratigraphic correlation across various locations are often given formal recognition and names Murphy and Salvador (1999). noted that certain beds serve as key (or marker) beds, which are important components of the stratigraphic framework because these distinctive bed properties make them useful for correlation over wide areas. These are very important units for understanding sedimentary environments and stratigraphy, too in order to detail out geological time frames. Improved geological studies, stratigraphic applications, detailed classification, description of the beds enhance accuracy and efficiency.

### 3.4.6 Level 6: Flow

A flow in volcanic lithostratigraphy is a distinct extrusive volcanic mass that can be distinguished from other flows with which it may interact by its texture, composition, or other distinct intrinsic and extrinsic properties! Because only flows with significant unique features and large areal extent can be identified, it is possible to identify individual units as named lithostratigraphic members. According to Murphy and Salvador (1999), the named flows represent geological data and allow us to learn more about volcanic structures and their distribution. More detailed information on lithostratigraphic groups of volcanic rocks, including details on how to classify ”flows”, will provide a broader perspective for a better understanding of massive bodies and necks. Murphy and Salvador (1999) explain that not all of these units are recognized, with only the most peculiar or universal flows being given legal personality. By following strict criteria for naming flows, geologists can comprehensively study and document the complex relationships that govern volcanic activity through time.

# Chapter 4

# Discussion

## 4.1 Proposal for Classification of Volcanic Lithostratigraphic Units

Based on the above analysis some of non-hierarchical units and a hierarchical classification method are established below. This scheme is intended to encapsulate the complexities and characteristics of volcanic lithostratigraphic units and to provide a coherent and consistent framework for their classification and interpretation. The proposed system brings together key geological characteristics and processes that are central in understanding the development of volcanic systems through time. Classification of the depositional environment in this way permits more faithful geological maps and study. Next up, the mechanics of that hierarchical framework and how it applies to a consideration of volcanic materials in Ecuador.

### 4.1.1 Level 1: Supersyntheme

By examining earlier defined terms and attempting to build upon them, a comprehensive framework that illustrates the complexity, as well as variation in volcanic deposits, has been derived — all for obtaining a composite definition meant to encompass key features of lithostratigraphic units related to volcanism at Level 1. This approach serves to ensure that characteristics of the natural world that are pivotal in understanding volcanic systems are captured and properly classified. In volcanic stratigraphy, a Supersyntheme is defined as the lithostratigraphic unit in which two or more Synthemes (level 2) are included due to having curious geological characteristics. It contains rock formations generated by a volcanic arc located stateside and overseas over periods of thousands to millions of years. The groups each maintain their distinctive features within the Supersyntheme. These are very significant when looking at and categorizing volcanic systems, as these groups have deposited to different settings (e.g., how you formed them), in different environments (regarding the geographic setting), or from various histories of eruptions. It is an integrated approach and makes a strong foundation for the study of complex volcanic arcs orogenesis by this overall methodology, in addition to stratigraphic units and examination of geological formations formed due to volcanism. At the same time, it provides a view of volcanic sediments at a regional scale. It formed in various geological environments between periods of volcanic eruption. Because they were erupting all the time, this takes into consideration the depositional history, or genetic past of a deposit, and any times in which it was quiescent. So, they must perform a study on the sequence of volcanic events and how weathering, erosion, and tectonic action have altered bands down over geologic time. This perspective is essential in order to glimpse how the system has evolved and behaved at long time scales. Volcanic lithostratigraphic units may be classified and interpreted using this framework, which unifies several essential features into a single concept. This thorough method ensures a broad grasp of intricate volcanic systems and supports specific mapping efforts and regional stratigraphic assessments. Maps scaled to 1:500,000 show distinguishable deposits at the Supergroup level. This level 1 would include Naranjal, Macuchi, Pisayambo, and Saraguro, which are currently considered formations or groups. These are important cases that have been recommended for inclusion within this first category. They include the volcanic deposits that were produced by their volcanic arcs, as well as the present volcanic arc and other equivalents that should be included at this level.

### 4.1.2 Level 2: Syntheme

In the context of volcanic lithostratigraphy, it corresponds to the combination of various volcanic formations. A synthemic unit is a broad stratigraphic framework that combines rigorous stratigraphic and volcanological criteria. At level two it recalls the definition of volcano, which states that a volcano is a geologic setting that is defined by three elements: magma, eruption, and edifice, regardless of its magnitude. This is adequate to establish the existence of a single of these variables as long as the others can be assumed to exist, to have been present, or to have the propensity to be present in future times (Borgia et al., 2010). Additionally, significant interruptions in depositional continuity, indicated by erosional periods or the presence of unconformities, are characteristic of such units. It is important to identify these breaks since they are fundamental in defining the exact bounds of each syntheme. The stratigraphic organization and interpretation of volcanic sequences are made easier by the identification of these traits, which allow for thorough and systematic research of the intricate volcanic history. By explaining how to recognize these breaks and what they mean to include all the deposits that were emitted from a volcano, this improved method highlights the importance of the Synthemic unit in the interpretation and study of volcanic systems, highlighting their use in Level 2 stratigraphic demarcation. The volcanoes and volcanic complexes that should be included at this level are the Cotacachi-Cuicocha Volcanic Complex, Imbabura volcano, Pichincha Volcanic Complex, Tungurahua volcano, Antisana volcano, among others. Additionally, foreign research on Mount Etna, Mount St. Helens, and the 18 volcanic centers within the Nicaraguan volcanic.

### 4.1.3 Level 3: Volcanic Formation

A volcanic formation is defined as a collection of volcanic deposits that have a consistent lithology or distinct lithological characteristics. These formations include all deposits formed during an eruptive phase of a volcano. They are characterized by unconformities that indicate periods of inactivity and collapse. This distinguishes them as a distinct lithostratigraphic unit within the field of volcanic stratigraphy. They are distinguished from adjacent formations by these specific characteristics. Because volcanic formations are considered mappable units, they must be represented cartographically at the map sizes typically used in a given region. The thickness of these strata can vary greatly, from less than a meter to several thousand meters, with considerable variability.

**Characteristics and considerations of application**

1. Lithological homogeneity is the uniformity of the lithological properties of the volcanic deposits inside a formation, including composition, texture, and structure. This uniformity aids in setting a formation apart from adjacent units.

2. Mappability: It is essential to be able to depict a volcanic formation on a map. This guarantees that the formation may be clearly recognized and investigated at many sizes, ranging from in-depth local maps to more comprehensive regional investigations.

3. Variable Thickness: Due to the dynamic nature of volcanic activity, the thickness of volcanic formations can vary greatly. This variance in thickness is a product of the geological processes that occurred during the formation's growth.

### 4.1.4 Level 4 Volcanic Member

The "Volcanic Member," a Level 4 lithostratigraphic unit, could be described as a discrete section within a volcanic formation that is distinguished by its distinct features resulting from a single eruptive event. These groups can be used to record and study the events of a volcanic complex accurately. This includes things like changes in mineralogy, consistency, and emplacement styles that are not always uniform throughout a formation. This subdivision allows geologists to plan better how and at what scale to sample rocks from an outcrop since they are not relying on the same mapped formation. Ash deposits indicate how long a given volcanic system has been associated with its parent caldera, and eruptive member units provide information on the dynamics of eruptivity away from the caldera. Understanding the interactions between these features provides insight into how volcanoes are built and how they evolve over time.

### 4.1.5 Level 5. No hierarchized detailed volcanic stratigraphic units ($\leq$ 1:25000)

In order to accurately represent the highly complex geologic history of a place at small local scales such as $\leq$ 1:25,000 when mapping any volcanic place, it is linked to a complete volcanic stratigraphic units studied. In order to get a more complex level of volcanic units, then it really comes down to doing detailed volcanic geology. The reason is that these units give us a better sense of volcanic behavior, and we can study the volcano by eruption as it is representative of a period of activity or inactivity. For features at this scale, the terminology used to describe and explain volcanic landforms is quite different. Such units are quiescent period units, single eruption units, or single flow units. In the case of basaltic lavas entries for multiple and sustained eruptions, eruptive pulse units and volcanic activity units were defined as long periods of frequent unrest episodes characterized by ”persistent strombolian generally explosive, and tephrostratigraphic units. Mapping and analysis of these units provide valuable insights into the history of volcanic systems by directly linking them to certain specific aspects that can be studied in detail. Higher-level units, such as the Volcanic Bed Unit and the Volcanic Flow Unit, have also been studied in depth. However, these units are highly correlated with syn-depositional tectonism because they contain unique lithological features that help in recognizing the geological cross section. In addition to improving the accuracy of maps, it also improves our understanding of volcanic events. Applying the criteria of Murphy and Salvador (1999) to search, find, and assemble these units improves our understanding of volcanic processes through time, helps to link components identified in one area with similar features detected elsewhere.

### Volcanic Bed

A lithostratigraphic unit, VBU, is a unique and distinct layer in the volcanic rock column. This is what most people call these units when they are a geological name representing the setting, such as beds/chalks in volcanic sediments or key beds. In turn, these strange features tell us a lot about the rocks above volcanoes, which in turn allows us to find connections between different volcanic regions. Murphy and Salvador (1999) also advocate naming these beds in the formal literature so that they can be used as part of a larger stratigraphic framework. This allows a complete record of volcanic processes and their temporal distribution if volcanic bed units can be correctly identified.

### Volcanic Flow

It is a lithostratigraphic unit, an identifiable layer of rock that has properties unique to its composition and texture. These are volcanic flow units, which are classified as separate extrusive (volcanic rocks). These stations are only for significant, wide-area, and one-of-a-kind detail points. This ensures that they are formally accepted and can be in geological maps and publications. According to Murphy and Salvador (1999), the systematic approach in which naming conventions are applied to these designations helps us broaden our understanding of volcanic formations and their distribution around the globe.

### Volcanic Activity Unit

One section within volcano stratigraphy has to do with specific eruptions and their products. This is the unit that teaches how to identify and define the different results of a volcanic explosion. For instance, Martí et al. (2018) made use of Volcanic Activity Units to isolate the stages and behaviors that occur during an eruption in a volcanic system.

### Individual Eruptive Unit

A more specific division of volcanic layers that originated from the same [eruptive] event. This unit is interesting to geologists because they can study and then draw or infer which specific eruption it represents to constrain better how these eruptions fit into their model of an entire volcanic complex. Martí et al. (2018) recently demonstrated the power of this technique by analyzing earthquake layers in the Las Cañadas crater in Tenerife, validating a new approach to individual eruptive units.

### Quiescence Period Unit

This unit of study introduced areas where a volcano may not be erupting, or it is between eruptions. Because the Quiescence Upholstered Units can show sequential volcanic action when times of rest occur, it is of considerable help in identifying and recording. According to Martí et al. (2018), Quiescence Period Units are used loosely to indicate time between volcanos that is relatively calm - a concept that was born from how volcanic systems function.

**Tephrostratigraphy Unit**

This unit is related with volcanic tephra layers, focusing on how they fit together and how to understand them. Tephra layers in different levels of rock, are used for finding how to identify and relate such layers. Tephrostratigraphy units were used by Martí et al. (2018) to work out the connections between tephra layers in their geological studies.

## 4.2 Application in specific case studies from Ecuador

In this proposed model, the goal is develop an integrated system that, as complex and varied as a volcanic series can be. The main aim is to improve the current classification systems for the Ecuadorian volcanic series. Doing so will harmonize them with international standards and take into account only the peculiarities of this tract, which is quite difficult to achieve. This innovative method focuses on aspects of great geological importance for understanding the formation of volcanic structures, their evolution over time, and their relationship to each other. This approach ensures that categories can be modified to fit different volcanic environments. Such variation provides easier material for study and more favorable conditions for controlling these ever-changing natural systems.

### 4.2.1 The Cotacachi-Cuicocha complex classification application

The application of the proposed classification framework to the Cotacachi-Cuicocha Volcanic Complex (CCVC) illustrates the practical utility of the new classification framework for volcanic lithostratigraphic units as is detailed in the Table 4.1. This methodology integrates global benchmarks with the distinctive features of the Ecuadorian volcanic arc, establishes a consistent framework for accurate classification and comprehensive analysis of volcanic formations. The objective of adopting this categorization is to elucidate the complex geological history of the CCVC, encompassing the diverse range of volcanic deposits and facilitating a comprehensive examination of its eruptive activities. The application of this framework to the CCVC serves as an illustration of its suitability for use in other volcanic settings.

**Level 1: Supersyntheme**

Quaternary Volcanic Arc.

**Level 2: Syntheme**

Cotacachi-Cuicocha Volcanic Complex: This unit integrates various volcanic formations from the complex, encompassing proximal and distal deposits formed over thousands to millions of years (M. Almeida et al., 2023). As a synthemic unit, it provides a stratigraphic framework that combines rigorous stratigraphic and volcanological criteria. It considers the presence or potential presence of magma, eruptions, and volcanic edifices. Significant interruptions in depositional continuity, such as erosional periods or unconformities, defining its boundaries (Sierra et al., 2021).

**Level 3: Volcanic Formation**

Cotacachi Syntheme: This synthemic unit encompasses the diverse volcanic formations associated with the Cotacachi stratovolcano, distinguished by its andesitic lava flows and associated deposits. The Cuicocha Syntheme: This synthemic unit is dedicated to the deposits associated with the Cuicocha caldera, encompassing explosive phases and the formation of post-caldera domes (Wolf and Yerovi).

**1. Cotacachi Volcanic Formation**

- **Type of volcano:** Stratovolcano.
- **Chemical composition:** Primarily andesites, with associated lava flows and deposits.
- **Volume of the volcano:** Approximately $56 \pm 4$ km$^3$.
- Geological characteristics: Includes a variety of lava flows and pyroclastic deposits that reflect its eruptive history.
- **Age:** Construction began around $173 \pm 4$ ka.

**2. Cuicocha Volcanic Formation**

- **Type of volcano:** Volcanic caldera.
- **Chemical composition:** Explosive deposits, including andesites and dacites.
- **Volume of the volcano:** Caldera of approximately 4.2 ± 0.1 $km^3$.
- **Geological characteristics:** Comprises explosive phases and the formation of post-caldera domes (Wolf and Yerovi).
- **Age:** The most recent explosive activity is dated to approximately 2980 ± 30 years BP.

**Level 4: Volcanic Member**

- **The Cotacachi Basal Volcanic Member,** the initial phase of construction is the defining characteristic of this member, which includes andesitic lava flows and isolated basaltic-andesitic lavas, is a stratigraphic unit that can be found within the aforementioned formation. A discrete section within the Basal Cotacachi Formation is distinguished by specific eruptive features and an age of 173 ± 4 ka.
- **The Upper Cotacachi Volcanic Member,** this member encompasses andesitic lava flows that are younger than 108 ± 6 ka, according to their studies. The dacitic Piribuela dome, which dates to 65 ± 2 ka. Piribuela dome is characterized by the initial phase of construction, comprising andesitic lava flows and isolated basaltic-andesitic lavas. The younger andesitic lava flows and the dacitic Piribuela dome composes this formation, revealing the different stages of volcanic activity.
- **The Cuicocha Pre-Caldera Member**
  It is characterized by the initial phase of construction, composed by andesitic lava flows and isolated basaltic-andesitic lavas. This formation encompasses the deposits associated with the explosive eruption that formed the Cuicocha caldera and the subsequent post-caldera dome (Sierra et al., 2021). This member represents the deposits that were formed prior to the formation of the caldera, including materials from the pre-caldera Cuicocha dome (M. Almeida et al., 2023).

- **The Post-Caldera Member,** this member encompasses the Wolf and Yerovi domes, which were emplaced subsequent to caldera formation (R. Almeida & Rengel, 2020).

**Level 5: Stratigraphic Units**

These detailed units have been analyzed by M. Almeida et al. (2023): Alluvial and Colluvial Deposits: These deposits are characterized by a mixture of fine to coarse materials, reflecting the dynamic processes of erosion and sedimentation in the volcanic landscape. Undifferentiated, Reworked Volcanoclastic Deposits: the deposits are not distinctly classified and may contain a mix of ash, pumice, and other volcanic fragments.

- **Cuicocha Pyroclastic Density Currents,** these deposits are characterized by their high-energy flow features and can include a mix of ash, pumice, and other volcanic materials.
- Cuicocha Pre-Caldera/Block and Ash Deposits, characterized by its andesitic composition and the eruptive features leading up to the caldera formation.
- **Lava Flows of the Summit,** characterized by their composition and flow morphology, reflecting the eruptive history of the summit area.
- **Lahar Deposits of Cotacachi,** deposits characterized by their flow features and can vary in composition depending on the source materials.
- **Pyroclastic Deposits of Cotacachi,** characterized by a range of particle sizes from fine ash to larger volcanic fragments.

**Units:**

- **Verde Tola Unit**, includes volcanic materials associated with the Verde Tola area, characterized by its specific mineralogy and eruptive history.
- **Northeastern Debris Avalanche Deposits**, conformed by deposits resulting from debris avalanches that occurred in the northeastern part of the volcanic complex, characterized by their chaotic arrangement of volcanic materials.

- **Northwestern Debris Avalanche**, deposits from debris avalanches in the northwestern area, characterized by similar chaotic features and composition as the northeastern deposits.

**Dome Units:**

- **Piribuela Dome**, encompasses the lava flows associated with the Piribuela dome, characterized by its dacitic composition and eruptive history.
- **Loma Negra Dome**, includes the deposits and lava flows associated with the Loma Negra dome, noted for its distinct mineral assemblage and eruptive features.
- **Muyurcu Dome,** includes the andesitic lava flows associated with the Muyurcu dome, noted for their distinct mineral assemblage and morphology.
- **Cuicocha Pre-Caldera Dome,** represents the deposits and lava flows associated with the pre-caldera Cuicocha dome, characterized by its andesitic composition and the eruptive features leading up to the caldera formation.

**Post-caldera Domes**

- **Wolf Dome,** includes the post-caldera lava flows and deposits associated with the Wolf dome, characterized by its morphology and eruptive characteristics following the caldera-forming event.
- **Yerovi Dome,** encompasses the lava flows and deposits related to the Yerovi dome, which were emplaced after the caldera formation, characterized by their unique textural features and composition.

There are additional units classified within Level 5 that were formed prior to the development of the Cotacachi Volcanic Formation, which have been dated to the Tertiary period.

- **Apuela Batholith Unit**, represents a large granitic body characterized by its extensive exposure and massive volume. It consists primarily of granitic rocks with a mineral assemblage of quartz, feldspar, and biotite.

- **Silante Unit**, includes volcanic materials associated with the Silante area, characterized by its specific geological features and composition.
- **Cala Unit**, encompasses volcanic deposits associated with the Río Cala area, characterized by its unique mineralogy and eruptive history.
- **Natividad Unit**, includes volcanic materials associated with the Natividad area, characterized by its specific geological features and composition.
- **Pallatanga Unit**, encompasses volcanic deposits associated with the Pallatanga area, characterized by its unique mineralogy and eruptive history.

The following is a summary of the proposal applied in the Cotacachi-Cuicocha Volcanic Complex, in table 4.1.

| Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|---|---|---|---|---|
| Supersyntheme | Syntheme | Volcanic Formation | Volcanic Member | Stratigraphic Units |
| Quaternary volcanic arc | Cotacachi-Cuicocha Volcanic Complex | Cotacachi | Basal Cotacachi | Muyurcu Dome<br>Loma Negra Dome<br>Verde Tola<br>NE Debris Avalanche Deposits |
| | | | Upper Cotacachi | Piribuela Dome |
| | | Cuicocha | Pre-Caldera | Cuicocha Pre-Caldera Dome |
| | | | Post-Caldera | Yerovi Dome<br>Wolf Dome |

Table 4.1: Application of the proposal to the Cotacachi-Cuicocha Volcanic Complex (CCVC)

### 4.2.2 Pichincha volcanic complex application

The Pichincha Volcanic Complex, located in the Ecuadorian Andes, importance related with their volcanic activity, especially due to its proximity to the city of Quito. It analyses examines the eruptive history and lithostratigraphic units of the complex, focusing on the eruptions of Guagua Pichincha and the older Rucu Pichincha. By using a classification system that combines local geological features with global volcanic standards, highlight the different phases of volcanic activity and the types of deposits produced, included as a summary in the Table 4.2.

**Level 1: Supersyntheme**

Quaternary Volcanic Arc.

**Level 2: Syntheme**

Pichincha Volcanic Complex: This unit incorporates all volcanic deposits from the Pichincha complex, it represents the entire geological history and eruptive activity of the complex, encompassing proximal and distal deposits formed over a period of thousands to millions of years.

**Level 3: Volcanic Formation**

**Guagua Pichincha**

Encompasses the diverse volcanic formations associated with the Guagua Pichincha stratovolcano, distinguished by its dacitic lava flows and explosive deposits.

- **Type of volcano:** Stratovolcano.
- **Chemical Composition:** Primarily dacites, with associated lava flows and explosive deposits.
- **Volume of the volcano:** Approximately 30 $km^3$ (estimated).
- **Geological Characteristics:** Characterized by explosive eruptions and dome-building phases, with significant pyroclastic flow deposits.
- **Age:** Construction began around 60 ka.

**Rucu Pichincha**

Includes the different types of volcanic rocks that are connected to the Rucu Pichincha stratovolcano. Andesitic lava flows and explosive deposits define these rocks. They were formed over millions of years by the earth's geological past. This includes the andesitic lava flows and the explosive phases that occurred in conjunction with their deposition.

- **Type of volcano:** Stratovolcano.

- **Chemical Composition:** Primarily andesites, with associated lava flows and deposits.
- **Volume of the volcano:** Approximately 56 ± 4 $km^3$.
- **Geological Characteristics:** Includes a variety of lava flows and pyroclastic deposits that reflect its eruptive history.
- **Age:** Construction began around 173 ± 4 ka.

**Level 4: Volcanic Member**

- **Lower Rucu Volcanic Member:** A discrete section within the Lower Rucu Volcanic Formation is distinguished by specific eruptive features and ages, including the oldest lava flows, which have been dated at approximately 850–600 ka. The initial phase of construction is the defining characteristic of this formation, which compose unvaried lava sequences and sparsely interlayered breccias from the lower Rucu edifice.
- **The Upper Rucu Volcanic Member,** is characterized by the presence of lava sequences and breccias from the upper Rucu edifice. Including younger andesitic lava flows and associated deposits, reflecting the subsequent stages of volcanic activity at Rucu Pichincha. This member constituted by andesitic lava flows younger than 600 ka and reflects the more recent eruptive history of Rucu Pichincha.
- **Guagua Pichincha Pre-Collapse Volcanic Member:** This member represents the deposits formed prior to the major sector collapse, including materials from the early explosive phases, encompasses the deposits associated with the explosive eruptions that formed the Guagua Pichincha stratovolcano, including pyroclastic flow deposits and dome-building events.

The following is a summary of the proposal applied in the Pichincha volcanic complex, in table 4.2.

| Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|---|---|---|---|---|
| Supersyntheme | Syntheme | Volcanic Formation | Volcanic Member | Stratigraphic Units |
| Quaternary volcanic arc | Pichincha Volcanic Complex | Guagua Pichincha | Cristal | Active Dome complex |
| | | | | Río Cristal pyroclastic flow series |
| | | | Toaza | Verde Tola |
| | | | | Toaza debris |
| | | | | Toaza Pyr. sequence |
| | | | Main Guagua Pichincha | Lava flows and domes |
| | | | | DAD1 |
| | | | | Lloa fan |
| | | | | Summit domes |
| | | | | Singuna flow |
| | | | | DAD 0 |
| | | | | Basal stratocone |
| | | Rucu Pichincha | Terminal Rucu | The Rucu Dome |
| | | | Upper Rucu | Lavas |
| | | | Lower Rucu | Lava flows |
| | | | El Cinto | Ungui dome |
| | | | La Esperanza | Wolf Dome |

Table 4.2: Application of the proposal to the Pichincha Volcanic Complex

### 4.2.3 Application of the proposal to Tungurahua volcano

The Tungurahua volcanic complex, located in the central zone of Ecuador, shows a dynamic nature of stratovolcanoes in the Andes. In this study, is considered the eruptive history and lithostratigraphic units that make up Tungurahua. By applying a classification framework that combines local geological characteristics with global volcanic standards, we aim to shed light on the different phases of volcanic activity—Tungurahua I, II, and III, the variety of deposits it has produced, mentioned accordingly in the Table 4.3. Their location within the Ecuadorian Volcanic Chain is represented in the Fig. 4.1

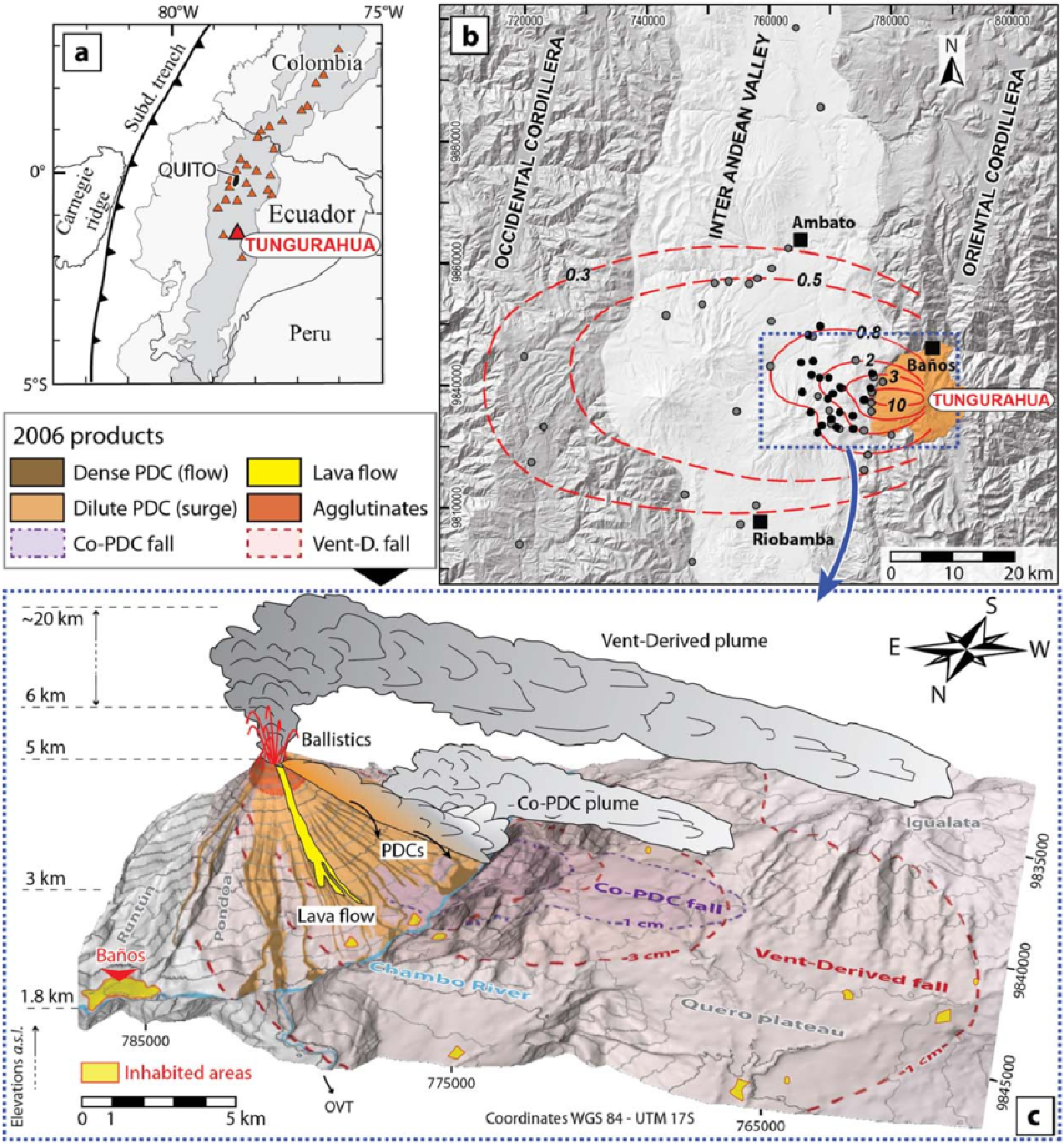


Figure 4.1: Location of Tungurahua volcano within the Ecuadorian volcanic arc (Taken from: J. Bernard et al. (2016))

**Level 1: Supersyntheme**

Quaternary Volcanic Arc.

**Level 2: Syntheme**

**Tungurahua volcano:** This unit incorporates all volcanic deposits from Tungurahua, encompassing proximal and distal deposits formed over the course of the volcano's eruptive history. This represents the geological evolution and activity of the volcano.

**Level 3: Volcanic Formation**

**Tungurahua I Volcanic Formation:** This formation is distinguished by its initial construction phase and composed by andesitic lava flows and deposits from the first edifice, with a total volume of approximately 124 ± 74 $km^3$.

- **Type of volcano:** Stratovolcano.
- **Chemical composition:** Composed primarily of andesitic lava flows and deposits.
- **Volume of the volcano:** Approximately 124 ± 74 $km^3$.
- **Geological characteristics:** Characterized by its initial construction phase with various lava flows and deposits from the first edifice.
- **Age:** The formation represents the earliest phase of volcanic activity.

**The Tungurahua II Volcanic Formation** is characterized by the construction of a new edifice following a significant by sector collapse. It encompasses deposits from the second phase of activity, including lavas and pyroclastic deposits from the current cone. The formation's total volume is estimated to be approximately 24 ± 4 $km^3$. Deposits from the Tungurahua II phase, are dated between 33 ka and 3 ka. These deposits are characterized by explosive eruptions and lava flows.

- **Type of volcano:** Stratovolcano.
- **Chemical composition:** Includes andesitic lavas and pyroclastic deposits, primarily andesitic.
- **Volume of the volcano:** Estimated to be approximately 24 ± 4 $km^3$.

- **Geological characteristics:** Characterized by the construction of a new edifice following a significant sector collapse, with deposits reflecting explosive eruptions and lava flows.

- **Age:** Deposits are dated between 33 ka and 3 ka.

**The Tungurahua III Volcanic Formation** is characterized by the presence of andesitic lava flows and deposits from the third edifice, which was constructed after a major collapse. This formation contains the deposits from the current eruptive phase, including basaltic andesite to dacitic compositions, and is associated with the most recent deposits associated with the ongoing activity of Tungurahua, particularly those deposited since the last major collapse, which occurred approximately 3,000 ya.

- **Type of volcano:** Stratovolcano.

- **Chemical composition:** Contains andesitic lava flows and deposits, with basaltic andesite to dacitic compositions.

- **Volume of the volcano:** Not specifically quantified but includes the most recent deposits.

- **Geological characteristics:** Characterized by deposits from the current eruptive phase, associated with the most recent activity since the last major collapse approximately 3,000 years ago.

- **Age:** Associated with deposits since the last major collapse, which occurred approximately 3,000 years ago.

**Level 4: Volcanic Member**

- **Tungurahua III-1 Member,** spanning approximately 2300 to 1400 BP, is characterized by basic andesite lavas rich in olivine and pyroxene, with $SiO_2$ content ranging from 56.0 to 56.3 percent, featuring effusive episodes and large pyroclastic flows.

- **Tungurahua III-2 Member,** began around 1300 ya, is distinguished by repetitive pyroclastic episodes followed by lava flows, with predominant pyroclastic activity transitioning to effusive activity as the volcano heats and dries out, with eruptions occurring approximately every 100 years.

- **Upper Lava Flow,** conformed by the most recent lava deposits from Tungurahua summit, characterized by fresh surfaces and features like flow ridges. Composed of basaltic andesite to dacite. This upper part, includes the steep summit and flanks of the volcano, marked by slopes of about 40°. It features glacial erosion and deep fluvial incisions, reflecting the impact of past eruptions and environmental factors on the volcano's morphology.
- **Intermediary Lava Flow,** contains lava deposits between the upper and basal units. These flows are older than the upper flows but younger than the basal edifice, providing evidence of the volcano's eruptive history and magma evolution.
- **Basal Edifice,** represents the foundational structure of Tungurahua, comprising older lava flows and pyroclastic deposits. It is crucial for understanding the volcano's early growth and the geological history of the region, primarily consisting of andesitic to basaltic andesite materials.

The following is a summary of the proposal applied in the Tungurahua volcano, in table 4.3.

| Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|---|---|---|---|---|
| Supersyntheme | Syntheme | Volcanic Formation | Volcanic Member | Stratigraphic Units |
| Quaternary volcanic arc | Tungurahua volcano | Tungurahua I | Upper lava flow | Ulba plateau |
| | | | | Pondoa plateau |
| | | | | Runtún plateau |
| | | | Upper part | |
| | | | Intermediary | Runtún |
| | | | Basal edifice | Pondoa |
| | | | | Patacocha |
| | | | | Runtún |
| | | | | Ulba |
| | | Tungurahua II | - | - |
| | | Tungurahua III | Tungurahua III-1 | Juve Chico lava flows |
| | | | | Vazcun Lava flows |
| | | | | Las Juntas PF |
| | | | | La Piramide |
| | | | | Motilones |
| | | | | Las Juntas upper PF |
| | | | Tungurahua III-2 | Las Juntas PF |
| | | | | La Rea |
| | | | | Bomb-rich PF |
| | | | | Las Juntas PF sequence |

Table 4.3: Application of the proposal to the Tungurahua volcano

The summary tables of the categorization facilitate the visualization of information while also underscoring gaps in data, which might guide the development of future research, warranting more discussion in this area.

### 4.2.4 Application of the proposal to the Imbabura volcano

The Imbabura Volcanic Complex, situated in northern Ecuador, exemplifies the volcanic and tectonic processes characteristic of the Andes. This study focuses on the eruptive history and lithostratigraphic units that constitute Imbabura, utilizing a classification framework that integrates local geological features with established global volcanic standards. Examining the distinct phases of volcanic activity—Imbabura I and II—and the diverse deposits generated throughout its eruptive history summarized in the Table 4.4 according to the proposal classification.

**Level 1: Supersyntheme**

Quaternary Volcanic Arc.

**Level 2: Syntheme**

**Imbabura Volcanic Complex:** This supersynthemic unit involves all volcanic deposits associated with the Imbabura volcano, including proximal and distal deposits that have formed over thousands to millions of years. Representing geological history and eruptive activity of the complex, reflecting the interaction of various volcanic processes and tectonic influences.

**Level 3: Volcanic Formation**

**Imbabura I Volcanic Formation** This formation is distinguished by the initial construction phase of the Imbabura edifice and encompasses a range of volcanic deposits, including andesitic lava flows and debris avalanche deposits, which reflect the early eruptive history of the volcano.

- **Type of volcano:** Stratovolcano.
- **Chemical composition:** Primarily andesites, with associated lava flows and debris avalanche deposits.
- **Volume of the volcano:** Approximately $40 \pm 5$ km$^3$.
- **Geological characteristics:** Encompasses a range of volcanic deposits, including andesitic lava flows and debris avalanche deposits, reflecting the early eruptive history of the volcano.
- **Age:** Construction began around $173 \pm 4$ ka.

**The Imbabura II Formation** is characterized by the deposits associated with the more recent eruptive phases of the Imbabura volcano. These deposits include lavas and domes, varying in their lithological and geochemical characteristics. The formation is divided into three distinct units, designated Imbabura II.1, II.2, and II.3, which reflect the repetitive eruption of lavas and domes.

- **Type of volcano:** Stratovolcano.
- **Chemical composition:** Characterized by lavas and domes with varying lithological and geochemical characteristics.

- **Volume of the volcano:** Approximately 16 ± 3 $km^3$.
- **Geological characteristics:** Divided into three distinct units: Imbabura II.1, II.2, and II.3, reflecting the repetitive eruption of lavas and domes throughout its history.
- **Age:** The eruptive phases of Imbabura II are more recent compared to Imbabura I, with significant activity occurring in the last 30,000 years.

**Level 4: Volcanic Member**

- **The Imbabura II.1 Volcanic Member**, is marked by specific eruptive features and ages, including the deposits from the earliest eruptive events. This member encompasses the extensive sequence of lava flows and domes that filled the depression resulting from the landslide.
- **The Imbabura II.2 Volcanic Member,** encompasses the lava dome/flow complex located in the high northeast flank of the volcano, which represents the later stages of eruptive activity.
- **The Imbabura II.3 Volcanic Member,** represents the dome complex in the middle SSW flank of Imbabura and includes deposits derived from block-and-ash flows and explosive eruptions.

The following is a summary of the proposal applied in the Imbabura volcano, in table 4.4.

| Level 1 | Level 2 | Level 3 | Level 4 | Level 5 |
|---|---|---|---|---|
| Supersyntheme | Syntheme | Volcanic Formation | Volcanic Member | Stratigraphic Units |
| Quaternary volcanic arc | Imbabura Volcanic Complex | Imbabura I | Imbabura I lavas | |
| | | | Imbabura DAD | |
| | | Imbabura II | Imbabura II-1 | lava flows |
| | | | | alluvial dep. |
| | | | Imbabura II-2 | alluvial dep. |
| | | | | BAFs |
| | | | | lava flows |
| | | | Imbabura II-3 | BAFs |
| | | | | lava flows |
| | | Cubilche | Post-avalanche edifice | |
| | | | Cubilche DAD | |
| | | | Pre-avalanche edifice | |

Table 4.4: Application of the proposal to the Imbabura volcano

## 4.3 Evaluation of Effectiveness and Relevance in Describing Proximal Volcanic Deposits

An accurate proposal for classification and description of volcanic deposits is required for understanding volcanic evolution, an regarding to the developing of uniform volcano-geological maps, assessing hazards, and making informed land-use decisions.

The proposed method emphasizes the multidisciplinary integration of volcanic, stratigraphic, petrologic, and morphologic information. The classification allows a thorough understanding of proximal deposits, as many data and tools are used in their interpretation, and depicts the complexity and diversity of these deposit types. A combination of field observations and laboratory analysis enables a successful classification. This dual approach ensures proper documentation and measurement of the depositional morphology, for better groupings.

The proposed categorization method is a very promising and well tested tool to map the intrinsic geological properties of such areas in other volcanic environments in Ecuador. The case studies are presented to show that the method can be used for better geological mapping and hazard assessment by focusing on the examples of CCVC, Imbabura volcano in Ecuador; Tungurahua, Pichincha volcanoes.

Although the proposed classification method offers significant improvements, its limitations should be acknowledged. Because volcanic depositional and processing regimes are inherently highly variable, it is conceivable that the classification criteria may require frequent adjustments. Further case studies will be completed, and new research on volcanic geology should be incorporated into the verification of the system.

## 4.4 Practical recommendations for the implementation in volcanic risk management and geological mapping

The implementation of a consistent categorization system facilitates the exchange of information regarding volcanic dangers between researchers and local populations, thereby enhancing the relevance of volcanic hazard assessment. The method facilitates the dissemination of information regarding potential hazards associated with nearby volcanic deposits by providing precise definitions and categorizations. Furthermore, the value of the proposed method extends to land use planning, as precise descriptions of nearby deposits inform decisions regarding infrastructure development and risk reduction strategies.

# Chapter 5

# Conclusions and Recommendations

## 5.1 Conclusions

- The implementation of a unified classification system has guided the recognition and inventory of lithostratigraphic units in Ecuador. It adapts global standards to the specific geologic context of Ecuador should lead to better comparability and analysis of volcanic deposits. Establishing a clear classification system will help researchers communicate their findings and allow data to be aggregated across many studies.
- The evaluation of existing national standards such as Instituto de Investigación Geológico y Energético, IIGE, showed that they are inadequate for application to Quaternary deposits. According to the existing criteria, volcanic units are generally classified based on their composition and the location of standard outcrops (e.g., Cotopaxi andesite or Chachimbiro dacite). However, this approach does not adequately account for the unique geologic features and eruptive history of certain volcanoes. In research and risk management, moreover, without a normalized systematization of criteria for categorizing them, it highlights more clearly an irregular one to address the volcanic heterogeneity present throughout Ecuador adequately.
- This proposal has been supported by the inclusion of specific examples from volcanoes such as Imbabura, Antisana, Cotacachi, Imbabura, Cotopaxi, and Tungurahua, which demonstrate their importance in the Ecuadorian geological context. These examples illustrate how the approach proposed here can provide a more consistent

framework to better categorize volcanic deposits in any setting based on their geological characteristics. This will help to define volcanic materials more accurately, and increase fluid communication between researchers in volcano risk assessment and management.

- It is clear that the volcanic map produced by the Instituto Geofísico (IG-EPN) needs to be reviewed. This map, which uses outdated categorization guidelines, is not an accurate representation of what we currently understand to be Ecuador's volcanic systems. A new unified map procedure is important because it can incorporate existing classifications and recently available geological information to improve resource management and reduce the exposure of structures to volcanic hazards in Ecuador. A new map would serve as a guide tool for emergency response planning, land use management, and public safety, ensuring that communities are better prepared for future volcanic hazards.

- The application of the classification method to different special cases-volcanic sites, such as Paricutín (Mexico), Cerro Negro (Ecuador-Colombia) and Kelimutu Indonesia, will provide a solid precedent for validating its effectiveness. Preliminary results show that the method is robust and can be applied in different geological environments, increasing its relevance to volcanology. Its successful application in diverse settings will require blueprints from field and model studies that test the hypotheses underlying the system, such as those in this study. The ability to learn about landscape structures has an impact on forming a foundation for being able to understand how different dynamics of global volcanic activity and initiate larger scale predictions, while also preparing to correctly apply this information when needed.

- The introduction of a specific classification system for Ecuador's volcanic regions is an interesting step forward in achieving more consistent and understandable geological maps. This program addresses deficiencies in the current categorization of volcanic formations, and promotes interaction between academia, local people, and government policy makers. The research provides a framework for more comprehensive, international standards-based studies and management of Ecuador's volcanic systems, guided by local geological knowledge.

## 5.2 Recommendations

- Implement the categorization method in various volcanic areas and develop case studies on specific examples like Paricutín (Mexico), Cerro Negro (Ecuador-Colombia), and Kelimutu (Indonesia) to validate its effectiveness in diverse settings. This approach will ensure the system is robust across different volcanic contexts.

- Consolidate geological data and perform geochemical and radiometric analyses to refine and validate the categorization criteria. By integrating comprehensive data collection with advanced laboratory techniques, the accuracy and reliability of the categorization system will be enhanced.

- Organize workshops and seminars with the geological community, and collaborate with experts in related fields to gather feedback and ensure a comprehensive approach. This engagement will help refine the system and promote its adoption across the geological community.

- Regularly update the categorization criteria based on new research findings, and integrate feedback from the geological community. Continuous improvement will keep the system relevant and aligned with the latest scientific developments.

- Develop instructional materials for geologists and students, and conduct public awareness campaigns to promote understanding of volcanic deposits and their importance in hazard assessment and land use planning. These efforts will support the widespread implementation and understanding of the categorization system.

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# Appendices

# .1 List of Acronyms

**BAFs** Block-and-Ash flows

**BP** Before present

**CCVC** Cotacachi-Cuicocha Volcanic Complex

**CPCVR** Cofre de Perote-Citlaltépetl Volcanic Range

**CGS** Czech Geological Survey

**DAD** Debris Avalanche Deposit

**DEM** Digital Elevation Model

**dep** deposits

**EPUs** Eruptive Pulse Units

**et al.** And others

**Fm** Formation

**GGP** Guagua Pichincha

**GIS** Geographic Information Systems

**GPR** Ground Penetrating Radar

**ICP-AES** Inductively Coupled Plasma Atomic Emission Spectroscopy

**ICS** International Commission on Stratigraphy

**IG-EPN** Instituto Geofísico de la Escuela Politécnica Nacional

**IIGE** Instituto de Investigación Geológica y Energética

**INETER** Instituto Nicaragüense de Estudios Territoriales

**IUGS** International Union of Geological Sciences

**ka** Thousand years ago

**LIDAR** Light Detection and Ranging

**Ma** Million years ago

**masl** Meters above mean sea level

**NVC** Nicaraguan Volcanic Chain

**SOB** Serdán-Oriental Basin

**St.** Saint

**TMVB** Trans-Mexican Volcanic Belt

**UBU** Unconformity Bounded Unit

**USA** United States of America

**VEI** Volcanic Explosivity Index

**VBU** Volcanic Bed Unit

**ya** Years ago