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Chapter 3

The Volcanic Front in Colombia: Segmentation and Recent and Historical Activity

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Abstract The active volcanic front in Colombia is divided into three main segments: The southern volcanic segment in the Western Cordillera and Inter–Andean Cauca–Patía Valley and the central and northern segments in the Central Cordillera, which are separated by a gap of 265 km. The recent volcanoes of the volcanic front are large polygenetic structures mostly built on the remnants of a Miocene – Pliocene volcanic terrain. The variety of eruptive styles and the composition and distribution of the volcanoes reflect the configuration of the Nazca Plate subducting beneath the continent, the interaction of plates and microplates at the NW corner of South America, and the tectonic structures in the Eastern Panamá Basin generated by the rupture of the Farallón Plate in the Miocene. Compositionally, the magmatic products of these volcanoes correspond to basaltic andesites, andesites, and dacites. Additionally, the most recent products of the volcanoes located in the central volcanic segment and at the ends of the other segments exhibit adakitic signatures and the most explosive behavior, usually of plinian type. The origin of the magmas has been attributed to several processes, including mantle melting, slab fluid–induced metasomatism of the mantle wedge, crustal contamination, magma mixing, and fractional crystallization. However, the processes that occur between the magma source and the lower crust, such as those related to the sizes and locations of magma chambers and the plumbing systems, are poorly understood. In the last 34 years, since the beginning of the systematic study of active volcanoes in 1985 and their continuous monitoring by the Servicio Geológico Colombiano, understanding of the superficial processes, stratigraphy, and eruptive history has progressed. Several of these volcanoes have a record of historical activity, such as Nevado del Ruiz, Puracé, Doña Juana, and Galeras. In recent years, some volcanoes have had eruptive activity, such as Nevado del Ruiz, Galeras, and Nevado del Huila, while others have shown signs of reactivation, such as Cerro Machín, Chiles–Cerro Negro, and Sotará. This chapter compiles the main characteristics of recent volcanism in Colombia in a tectonic context and summarizes the historical volcanic activity in this region.

Keywords: *active volcanoes, eruptive chronology, historical activity, andesite–dacite, adakite.*

Resumen El frente volcánico activo en Colombia se encuentra dividido en tres segmentos principales: el segmento volcánico sur en la cordillera Occidental y el Valle Interandino Cauca–Patía y los segmentos central y norte en la cordillera Central, los cuales están separados por gap de 265 km. Los volcanes recientes que constituyen el frente son grandes estructuras poligenéticas construidas en su mayoría sobre los remanentes de un terreno volcánico del Mioceno–Plioceno. La variedad de estilos

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eruptivos y la composición y distribución de los volcanes reflejan la configuración de la Placa de Nazca que subduce bajo el continente, la interacción de placas y microplacas en la esquina NW de Suramérica y las estructuras tectónicas de la Cuenca Oriental de Panamá, generadas por la ruptura de la Placa de Farallón en el Mioceno. Composicionalmente, los productos magmáticos de los volcanes que conforman el frente corresponden a andesitas basálticas, andesitas y dacitas. Además, los productos más recientes de los volcanes ubicados en el segmento volcánico central y en los extremos de los otros segmentos exhiben tendencias adakíticas y el comportamiento más explosivo, generalmente con erupciones plinianas. El origen de los magmas se ha explicado como el resultado de varios procesos, incluyendo fusión del manto, metasomatismo de la cuña mantélica inducido por fluidos de la placa que subduce, contaminación cortical, mezcla de magmas y cristalización fraccionada. Sin embargo, los procesos que ocurren entre la fuente magmática y la corteza inferior, como aquellos relacionados con tamaños y localizaciones de cámaras magmáticas y sistemas de alimentación, son poco conocidos. En los últimos 34 años, desde el comienzo del estudio sistemático de los volcanes activos en 1985 y su monitoreo continuo por parte del Servicio Geológico Colombiano, se ha avanzado en el conocimiento sobre los procesos más superficiales, la estratigrafía y la historia eruptiva. Varios de estos volcanes tienen registro de actividad histórica, entre ellos el Nevado del Ruiz, el Puracé, el Doña Juana y el Galeras. En los últimos años, algunos volcanes han tenido actividad eruptiva, como el Nevado del Ruiz, el Galeras y el Nevado del Huila, mientras otros han presentado signos de reactivación, como el Cerro Machín, el Chiles–Cerro Negro y el Sotará. Este capítulo compila las principales características del vulcanismo reciente en Colombia en un contexto tectónico y resume la actividad volcánica histórica en esta región.

Palabras clave: *volcanes activos, cronología eruptiva, actividad histórica, andesita–dacita, adakita.*

1. Introduction

The Colombian Andes is divided into three ranges, namely, the Eastern, Central, and Western Cordilleras, which are separated by inter–Andean valleys (Figure 1). Volcanic activity has persisted in this region since the Neogene, related to the orogenic paroxysm marked by the increase in volcanism in the late Miocene and the Pliocene (i.e., Ramos & Aleman, 2000; van Houten, 1976). The resulting volcanic products formed the currently eroded volcanic structures on which most of the Pleistocene – Holocene volcanic edifices have developed. This volcanism is part of the Northern Andean Volcanic Zone (Stern, 2004; Thorpe & Francis, 1979) related to the configuration and subduction of the Nazca Oceanic Lithospheric Plate under northern South America (Arcila & Dimaté, 2005; Cediel et al., 2003; Gansser, 1973; Lonsdale, 2005; Pennington, 1981).

Recent volcanoes in Colombia have well–preserved morphologies, shaped by a variety of eruptive styles, products, and compositions that have built volcanic complexes, volcanic chains, composite volcanoes, monogenetic volcanic fields, calderas, and domes. Following Siebert et al. (2011), Simkin & Siebert (1994), and Tilling & Punongbayan (1993), the Servicio Geológico Colombiano (SGC) considers recent volcanoes active if (1) they have exhibited eruptive activity in the last 10 000 years, (2) they have historical reports of eruptions, or (3) they register seismic activity, and exhibit fumaroles and thermal springs.

For the current state of active volcanoes, the SGC uses the following activity levels to communicate to the authorities and communities: Level 4 or green level for active dormant volcanoes; Level 3 or yellow level for awakening volcanoes; Level 2 or orange level for volcanoes in a pre–eruption state; and Level 1 or red level for erupting volcanoes.

In Colombia, these recent volcanoes compose the current volcanic front and are distributed in three segments (i.e., Hall & Wood, 1985) known as the southern volcanic segment, the central volcanic segment, and the northern volcanic segment. Most of the volcanoes reach elevations greater than 4000 masl above sea level and are located in the highest portions of the Central and Western Cordilleras, although the Galeras Volcanic Complex is located in the Inter–Andean Cauca–Patía Valley (Figure 1; Table 1). Additionally, there are monogenetic fields in a rear arc position (Figure 1) on the eastern flank of the Central Cordillera and in the Inter–Andean Magdalena Valley (see Monsalve–Bustamante et al., 2020).

The lithologies and ages of the basement, on which the volcanoes are developed, vary from metamorphic rocks including quartz–sericite schists, greenschists, phyllites, quartzites, amphibolites, marbles, metapelites, and gneisses of the Cajamarca

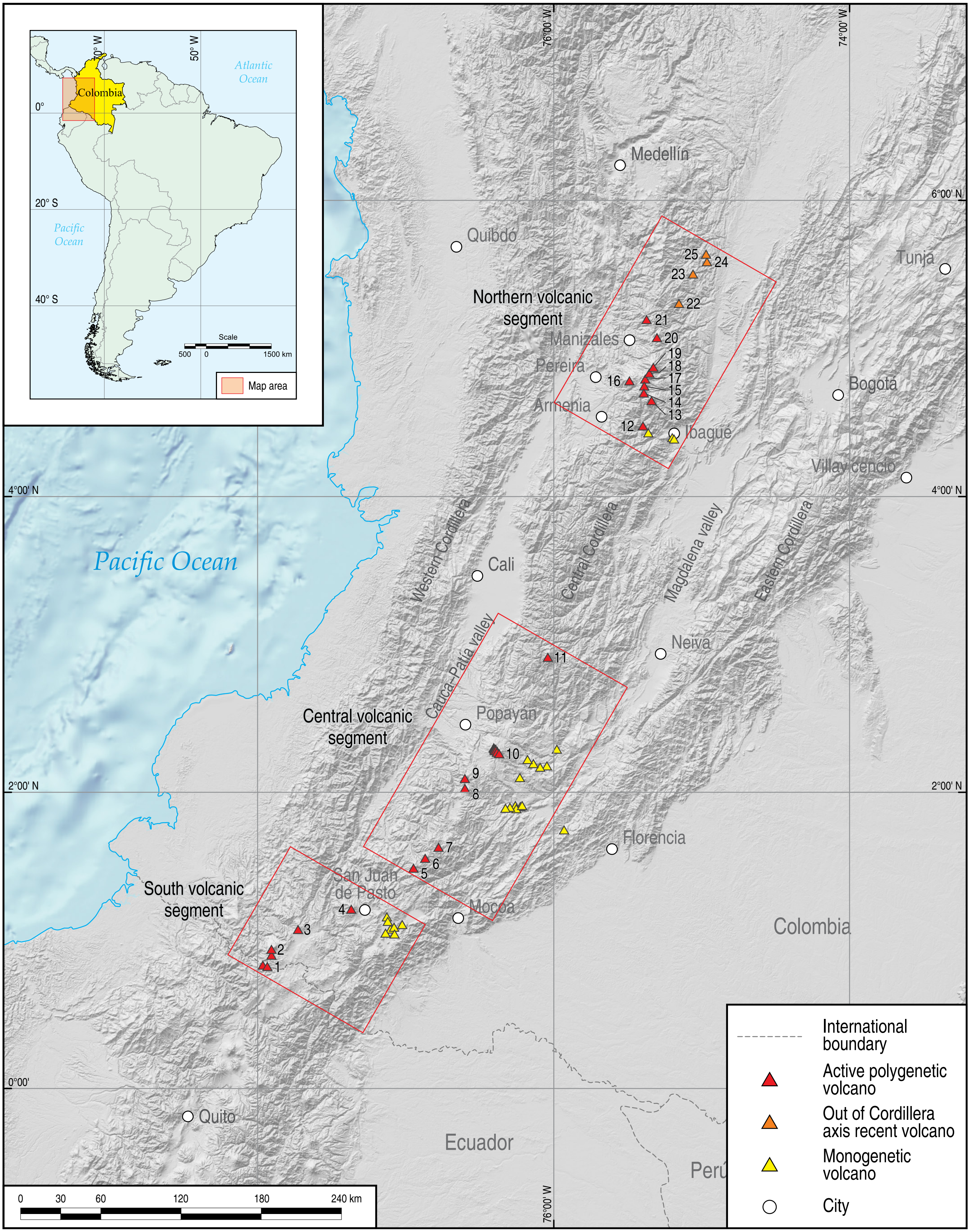


Figure 1. Location of recent volcanism in Colombia. Note the distribution of the volcanoes along the volcanic front and the volcanic gap between the central and northern segments. The numbers assigned to the volcanoes correspond to the list in Table 1.

Table 1. Recent volcanoes in Colombia are listed from south to north.

Volcano/complex name	Geographical coordinates		Elevation (masl)	Type
	Latitude N	Longitude W		
Southern segment				
(1) Chiles–Cerro Negro	0° 49’ 21.05”	77° 56’ 57.05”	4748	2 composite volcanoes
(2) Cumbal	0° 57’ 21.67”	77° 53’ 6.54”	4764	2 composite volcanoes plus other vents
(3) Azufral	1° 5’ 4.500”	77° 43’ 0.057”	4070	Composite (older); tuff ring–dome complex (current)
(4) Galeras	1° 13’ 16.90”	77° 21’ 33.18”	4276	Composite volcano built on horseshoe structures
Central segment				
(5) Doña Juana	1° 29’ 51.56”	76° 56’ 20.97”	4160	Composite volcano built on caldera remnant; dome complex (current)
(6) Ánimas	1° 33’ 58.22”	76° 51’ 17.93”	4160	Composite volcano; dome complex
(7) Petacas (?)	1° 37’ 20.22”	76° 50’ 34.54”	4000	Composite volcano; dome complex (?)
(8) Sucubún (?)	2° 01’ 7.11”	76° 34’ 23.36”	4080	Dome built on eroded caldera
(9) Sotará	2° 6’ 26.87”	76° 35’ 26.08”	4420	Dome complex and composite volcano
(10) Coconucos Volcanic Chain	2° 19’ 00.00”	76° 23’ 00.00”	4646	15 NW–SE aligned vents; composite
(11) Nevado del Huila	2° 55’ 25.80”	76° 1’ 42.92”	5364	Composite; N–S–aligned dome complex
Northern segment				
(12) Cerro Machín	4° 29’ 11.92”	75° 23’ 10.30”	2750	Tuff ring–dome complex
(13) Nevado del Tolima	4° 39’ 30.87”	75° 19’ 46.18”	5215	Composite volcano
(14) Nevado del Quindío (?)	4° 42’ 53.03”	75° 23’ 19.64”	4700	Composite eroded edifice; seismic activity registered
(15) Cerro España–Cerros de Alsacia	4° 45’ 17.00”	75° 22’ 18.62”	4533	Eroded caldera; small cones and domes aligned NNE
(16) Santa Rosa (?)	4° 47’ 48.28”	75° 27’ 50.02”	4600	Eroded caldera; seismic activity registered; hot springs
(17) Santa Isabel	4° 48’ 10.57”	75° 22’ 29.14”	4965	Composite; dome complex
(18) Cisne (?)	4° 50’ 33.43”	75° 21’ 8.65”	4700	Composite; dome complex
(19) Nevado del Ruiz	4° 53’ 35.11”	75° 19’ 8.99”	5321	Composite volcano; adventitious volcanoes and vents
(20) Cerro Bravo	5° 05’ 27.22”	75° 17’ 32.88”	4000	Dome complex
(21) Romeral (?)	5° 12’ 21.60”	75° 21’ 50.40”	3858	Eroded caldera; 7000 y BP age reported
Northern Central Cordillera (off the range axis)				
(22) Guadalupe (?)	5° 16’ 55.41”	75° 08’ 4.52”	2561	Dome complex
(23) El Escondido (*)	5° 31’ 15.45”	75° 02’ 40.15”	1624	Tuff ring–dome complex
(24) Berlín (*)	5° 35’ 20.83”	74° 55’ 51.10”	812	Maar
(25) San Diego (*)	5° 38’ 56.49”	74° 57’ 36.18”	1153	Pyroclastic ring–maar complex; intracrater tuff cone

Note: The numbers in parentheses identify the volcanic structures in Figures 1, 6, 16, 29.

(*) Recent volcanoes without confirmation of Holocene activity.

(?) Volcanoes without well–preserved morphology but with associated seismic activity or considered active in the literature.

Complex, and Mesozoic granite and metamorphic rocks in the Central Cordillera (Barrero, 1979; Gómez et al., 2015; Nelson, 1962) to accreted Cretaceous mafic crust in the Western Cordillera (Bourgois et al., 1982; Kerr et al., 1998).

Schmitt (1983) geochemically distinguished three compositional groups of Colombian volcanics: (1) alkali feldspar rhyolite (SiO_2 up to 77%) corresponding to Miocene ignimbrites exposed on both sides of the southern part of the Central Cordillera (Kroonenberg et al., 1981; Torres, 2010; Torres et al., 1999); (2) subalkaline volcanic rocks (quartz tholeiite to dacite, with SiO_2 between 54 and 65%) on the eastern axis and flank of the Central Cordillera; (3) alkaline volcanic rocks (olivine basalts to olivine–nepheline basalts) in the Upper Magdalena Valley. Marriner & Millward (1984) described upper Miocene tholeiitic basalts and basaltic andesites on the eastern flanks of the Western Cordillera, northern Colombia, and a continuation of subduction–related magmatism with the formation of dominantly andesitic and composite calc–alkaline stratovolcanoes along the axis of the Central Cordillera.

On the other hand, Droux & Delaloye (1996) distinguished two magma types in active volcanoes. Type I is represented by lavas from volcanoes in the central volcanic segment and characterized by high TiO_2, K, Ba, Rb, Sr; light rare earth elements (LREE) contents, and Ce/Yb ratios; as well as low heavy rare earth elements (HREE) contents and low Ba/La ratios. For these lavas, the authors suggested crustal contamination of the magmas due to the presence of the metamorphic basement in the Central Cordillera. Type II corresponds to lavas from volcanoes in the southern volcanic segment and features low TiO_2 contents, depleted K, Ba, Rb, and Sr, low Ce/Yb ratios, enriched HREE contents, and high Ba/La ratios, which according to the authors indicate limited participation of crustal material. In turn, Marín–Cerón (2004, 2007) attributed the generation of the magmas of the central and southern volcanic segments to the partial melting of the mantle wedge relatively enriched in components derived from the subducting plate.

Marín–Cerón et al. (2018) presented a petrographical and geochemical review of Northern Andes volcanism and explained the adakitic tendency of some of the volcanoes in Colombia as related to mantle–derived magmatism and H_2O–rich lower crustal interaction.

More recently, an adakitic chemical signature has been recognized in some volcanoes, although its origin is not yet well established (i.e., Borrero et al., 2009; Correa–Tamayo, 2009; Marín–Cerón et al., 2018). Adakites, first described by Kay (1978), are high–Mg andesites or dacites with low HREE and high Sr concentrations relative to normal calc–alkaline series lavas (Defant & Drummond, 1990). The origin of adakites is an area of active debate but is thought to involve melting of subducted oceanic crust that has been metamorphosed to eclogite. The production of adakites requires anomalous thermal conditions (Peacock, 1990), such as subduction and melting of young, warm lithosphere; subduction of older, colder lithosphere associated with unusual tectonics, e.g., slab windows or tears, that may allow hot mantle to flow up and around the edge of the torn subducted lithosphere (Davaille & Lees, 2004; Osozawa, 1997; Yogodzinski et al., 1995); and melting of lower continental crust associated with thickened upper crust or delamination (Kay et al., 2005).

Although the geochemical signatures of Ecuadorian and Colombian volcanism have been considered similar (i.e., Francis et al., 1977); Vanek et al. (1994) found differences in the compositions of recent volcanic rocks in Ecuador and southern Colombia (the southern volcanic segment) and suggested that calc–alkaline volcanism is related to different lithospheric plates. Furthermore, they argued that the anomalous enrichment of compatible and incompatible elements in andesites and dacites could be influenced by the structure of deep faults in the continental wedge.

2. Brief Historical Review of Knowledge about Colombian Volcanoes

The first reports on volcanic activity in Colombia correspond to pre–Hispanic oral traditions. Additionally, according to Quijano–Vodniza (2006), some petroglyphs found in southern Colombia represent the erupting Galeras Volcano (Figure 2). The observations of foreign naturalists contributed additional knowledge, and in the nineteenth and early twentieth centuries, they recorded valuable descriptions of some Colombian volcanoes. Compilations of historical volcanic activity have been developed by other authors (i.e., Espinosa–Baquero, 2011 and references therein). Recently, interdisciplinary archaeological and volcanological efforts have been carried out to identify the impact of volcanic eruptions on pre–Hispanic settlers (i.e., Cano et al., 2015; Posada, 2017; Salgado & Varon, 2019). These authors agree that in the northern volcanic segment of Colombia, almost continuous human occupation is observed that represents the Preceramic, Classic, Late, and Recent periods of the regional chronology, with a clear gap between the years 3500 and 2000 BC, probably due to eruptive activity and new climatic conditions.

Since the 1930s, exploration for natural resources, such as sulfur and semiprecious stones (Mercaderes garnet–bearing tuff), as well as geothermal exploration and regional cartographic works settlers, provided the first data on Colombian volcanoes (i.e., Arango & Ponce, 1980; Forero, 1956; Grosse, 1935; Hubach & Alvarado, 1932; Megyesi, 1962; Murcia & Marín, 1981; Organización Latinoamericana de Energía (Olade) & Geotérmica Italiana, 1982; Royo y Gómez, 1942a). In the 1980s, undergraduate, masters, and doctoral thesis contributed more specific knowledge on the subject: Herd (1974) and Thouret (1988) carried out studies of morphology, glaciology, tephra stratigraphy, and volcanic geology of the Ruiz–Tolima Volcanic Complex; Jaramillo (1980) studied the Nevado del Ruiz Volcano from the petrological point of view; and Lescinsky (1990a) carried out research on the Cerro Bravo Volcano. Ramírez (1982) delineated the main characteristics of the active volcanoes of Colombia; Flórez (1987) recognized and described important tephra layers in the Caldas and Antioquia Departments; and Calvache (1990, 1995) studied the Galeras Volcanic Complex. Works developing the first volcanic hazard maps expanded such knowledge (i.e., Cepeda & Murcia, 1988; Cepeda et al., 1985, 1986; Cortés & Calvache, 1997; Ingeominas, 1989; Ingeominas & Corporación Autónoma Regional de Risaralda (Carder), 1993; Monsalve & Méndez, 1988; Monsalve & Núñez, 1992; Monsalve & Pulgarín, 1993; Parra & Cepeda 1990).

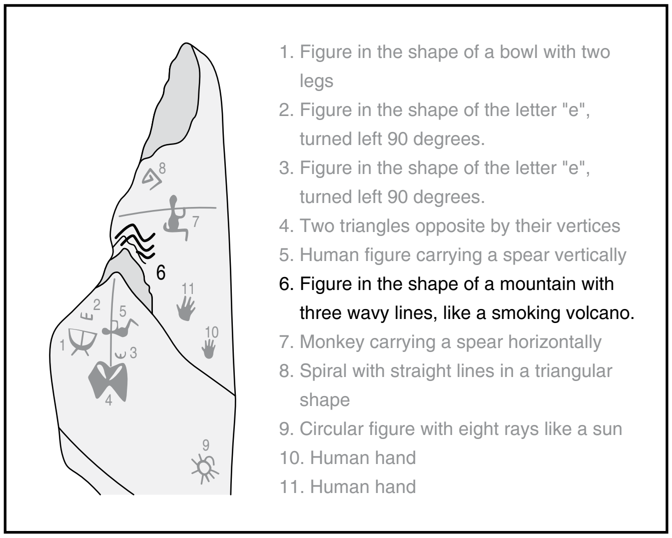


Figure 2. Pictograph of "El Higuerón", located in Mapachico (Pasto), showing the Galeras Volcano in activity: "6. Figure in the shape of a mountain with three wavy lines, like a smoking volcano" (Quijano–Vodniza, 2006). Modified from Santacruz–Moncayo (2009).

Despite reports of eruptions in Colombia, even from the sixteenth century, volcanoes were not studied with the aim of understanding their behavior and threats, and no monitoring of their activity was performed until the catastrophe caused by the eruption of Nevado del Ruiz on 13 November 1985, which demonstrated the need to study and monitor active volcanoes. Since then, the SGC has continuously monitored active volcanoes and, along with several national and foreign universities, has conducted research on volcanism in Colombia.

Currently, the Nevado del Ruiz, Galeras, and Nevado del Huila Volcanoes are at the yellow (or 3) level of activity. Due to increases and variations in the seismicity patterns, the Cerro Machín Volcano, the Chiles–Cerro Negro Volcanic Complex, and the Sotará Volcano are considered to have shown signs of reawakening since 2007, 2014, and 2016, respectively; therefore, their activity levels changed from green (or 4) to yellow (or 3) without presenting eruptive activity.

3. Tectonic Setting

Colombia is located in a complex plate boundary tectonic setting in the NW corner of South America (Figure 3). The region is dominated by a transpressive regime resulting from the convergence among the Nazca and Caribbean Plates, Panamá, and the North Andean Block, which is part of the South American Plate (Cortés & Angelier, 2005; Freymueller et al., 1993; Kellogg & Vega, 1995; Ramos 1999; Taboada et al., 2000; Velandia et al., 2005). The eastern edge of the North Andean Block defines the boundary of the South American Plate and extends NE from the Gulf of Guayaquil in Ecuador through the frontal fault zone of the Eastern Cordillera (Pennington, 1981) to Venezuela. The volcanism in this region is related to the oblique subduction of the Nazca Plate beneath the South American Plate.

The bathymetric characteristics of the Eastern Panamá Basin and the Panamanian Isthmus have affected the process of the Nazca Plate subducting under the South American Plate, thus determining the current configuration. The subduction of oceanic rifts (Gutscher et al., 1999; Hardy, 1991; Hey, 1977; Lonsdale 2005; Lonsdale & Klitgord, 1978) might also play a role in controlling the locations and compositions of volcanoes and the division into segments along the Colombian and Ecuadorian front arc, as invoked by Hall & Wood (1985), Marcaillou & Collot (2008), Marcaillou et al. (2006, 2008), and Pennington (1981).

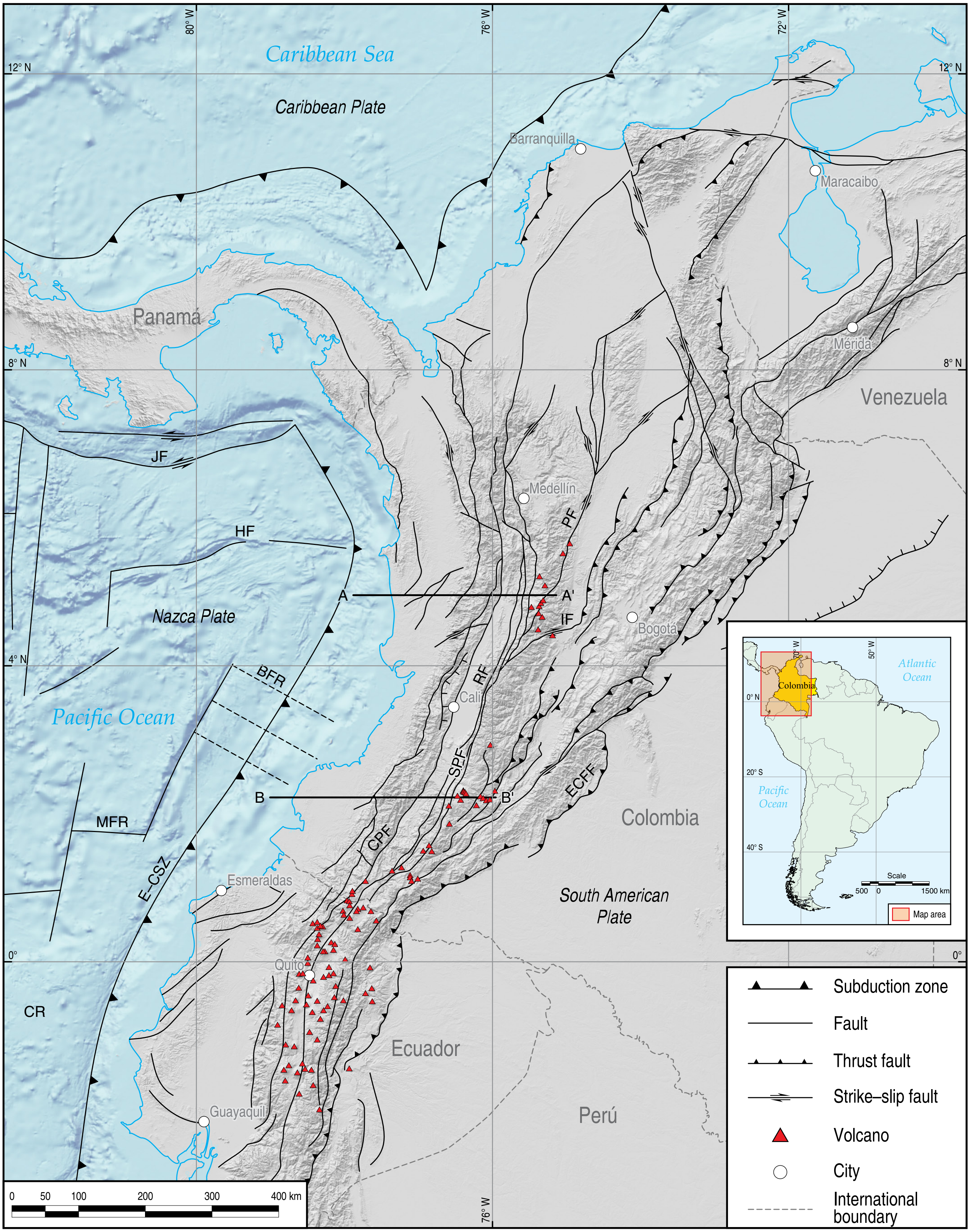
The subduction of the Carnegie Ridge in the E–NE direction beneath Ecuador and southern Colombia affects volcanism in this region (Barberi et al., 1988; Gutscher et al., 1999). The age of the subducting Nazca Plate increases from 10 to 25 Ma below the Northern Andean Volcanic Zone north of the Carnegie Ridge (Hardy, 1991; Lonsddale, 2005). The estimated convergence rates between the Nazca and South American Plates range from 5–7 cm/y (Freymueller et al., 1993; Kellogg & Vega, 1995; Trenkamp et al., 2002).

Pennington (1981) defined three segments in the subducting plate based on the hypocenter locations of earthquakes and the determination of focal mechanisms. From north to south, these segments are (1) the Bucaramanga segment, which is adjacent to the oceanic floor from the Caribbean to NE Colombia; (2) the Cauca segment, which is defined by intermediate–depth seismicity south of 5.2° N and corresponds to oceanic crust (Nazca Plate) subducting below South America at the Colombia–Ecuador Trench; and (3) the Ecuador segment, which dips towards the NE under central Ecuador. This author highlighted the lack of seismicity between 2° N and 2° S, which constitutes an aseismic region separating the Cauca and Ecuador segments along a zone corresponding to a subducted extinct spreading center.

Arcila & Dimaté (2005) more recently characterized the subduction and seismic sources in Colombia and defined three segments in the trench zone, which are described below:

In the northernmost segment between 5.5 and 7.5° N, the trench shows an azimuth of 310° and a length of 170 km and is bounded in the north by the Jordan Fault Zone and in the south in front of the Cabo Corrientes, where the Hey Fault converges, thus delimiting the sinistral boundary between the Nazca Plate and the Coiba Block defined by Adamek et al. (1988).

Figure 3. Northern Andes tectonic map and the location of volcanism. (HF) Hey Fracture; (JF) Jordan Fault; (BFR) Buenaventura Fossil Rift; (MFR) Malpelo Fossil Rift; (E–CSZ) Ecuador–Colombia Subduction Zone; (CR) Carnegie Ridge; (ECFF) Eastern Colombian Front Range Fault; (IF) Ibagué Fault; (PF) Palestina Fault; (RF) Romeral Fault; (SPF) Silvia–Pijao Fault; (CPF) Cauca–Patía Fault; (A–A'), (B–B') Cross sections shown in Figure 4a, 4b, respectively (modified from Kellog & Vega, 1995; Stern, 2004).



Caribbean Sea
Caribbean Plate
Barranquilla
Maracaibo
Panamá
Mérida
Venezuela
JF
HF
Medellín
PF
A
A'
IF
Bogotá
Nazca Plate
BFR
RF
Cali
Pacific Ocean
SPF
ECFF
B
B'
Colombia
MFR
CPF
E–CSZ
Esmeraldas
South American Plate
Quito
CR
Ecuador
Guayaquil
Perú
12° N
8° N
4° N
0°
80° W
76° W
72° W
0 50 100 200 300 400 km
Atlantic Ocean
Colombia
Pacific Ocean
0° N
20° S
40° S
70° W
50° W
Scale
500 0 1500 km
Map area
Subduction zone
Fault
Thrust fault
Strike–slip fault
Volcano
City
International boundary

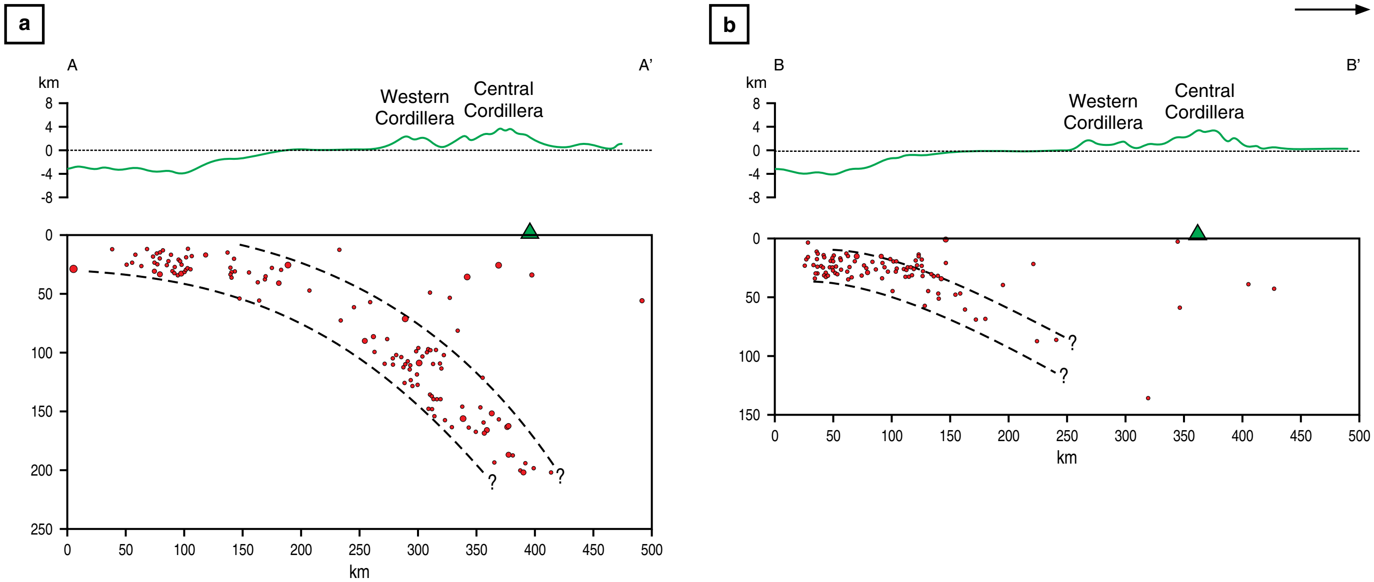


Figure 4. (a) Section showing the seismicity distribution and depth below central–western Colombia. **(b)** Section perpendicular to the trench showing the distribution of seismicity with depth under southwestern Colombia. At the top of the figure, a topographic profile is shown; the green triangle indicates the location of active volcanism. The locations of the sections are shown in Figure 3 (modified from Arcila & Dimaté, 2005).

In the central segment between 4.0 and 5.5° N, the trench shows an azimuth of 20° and is 160 km in length. The northern end is perpendicular to the Hey Fracture, and the southern limit is marked by a change in the direction of the trench at the Buenaventura Fossil Rift (78° W, 4° N) (Hardy, 1991). The seismicity between 60 and 210 km in depth defines a perpendicular section characteristic of a subduction zone, with a Benioff zone dipping at 40° and reaching a depth of 210 km under the Central Cordillera, where active volcanism in the northern volcanic segment is located (Figure 4a).

Finally, in the southernmost segment between 0 and 4° N, the trench shows a 40° azimuth from the Buenaventura Fossil Rift and has a length of approximately 550 km. The southern limit is marked by the NE end of the Carnegie Ridge. In the vertical section, the slab is horizontal for the first 100 km and then exhibits a 30° dip, penetrating to a depth of up 100 km below southern Colombia and the northern coast of Ecuador. This slab does not define a continuous Benioff zone under the active volcanic front (Figure 4b).

4. Volcanic Segments

The Colombian active volcanic front is divided into three segments defined by their geographical positions and limited by SE–NW lineaments, as proposed by Hall & Wood (1985). These authors defined seven transverse boundaries that divide the Northern Andean Volcanic Zone into segments parallel to the subduction of the Nazca Plate (Figure 5). Other authors have also highlighted the segmentation of the Colombian Andes by transverse faults with a SE–NW orientation (i.e., Cortés–del Valle, 1990; Lozano & Murillo, 1983; Page, 1983; Ujueta, 1993, 2001; Vargas & Mann, 2013). Cediel et al. (2003) and Marín–Cerón et al. (2018) emphasize the control of NNE paleosuture systems, along which these authors have reconstructed the Northern Andean Block, on the distribution of volcanism in the Northern Andean Volcanic Zone.

The southern volcanic segment, corresponding to the extension from the Ecuadorian volcanism, is located in the Western Cordillera and the Inter–Andean Cauca–Patía Valley. The central and northern volcanic segments are located on the Central Cordillera and are separated by a 265 km volcanic gap, in which the only volcanic edifice is the Nevado del Huila Volcano. Ojeda & Ottemöller (2002) noticed a low attenuation of Lg waves in this region, contrasting with the high attenuation to the north and south, and they concluded that the volcanic processes north and south of Colombia are independent; however, subsequent studies concerning this topic have not been carried out to explain the gap between the active volcanic segments.

4.1. Southern Volcanic Segment

The volcanic structures that make up the southern volcanic segment are between the limits defined by Hall & Wood (1985): limit F (Río Mira) to the south and limit E (Guairapungo) or the Manglares Fault of Marcaillou et al. (2006, 2008) to the north (Figure 5), and the volcanoes are located at distances between 240 and 250 km from the trench. Additionally, a group of monogenetic volcanoes is located to

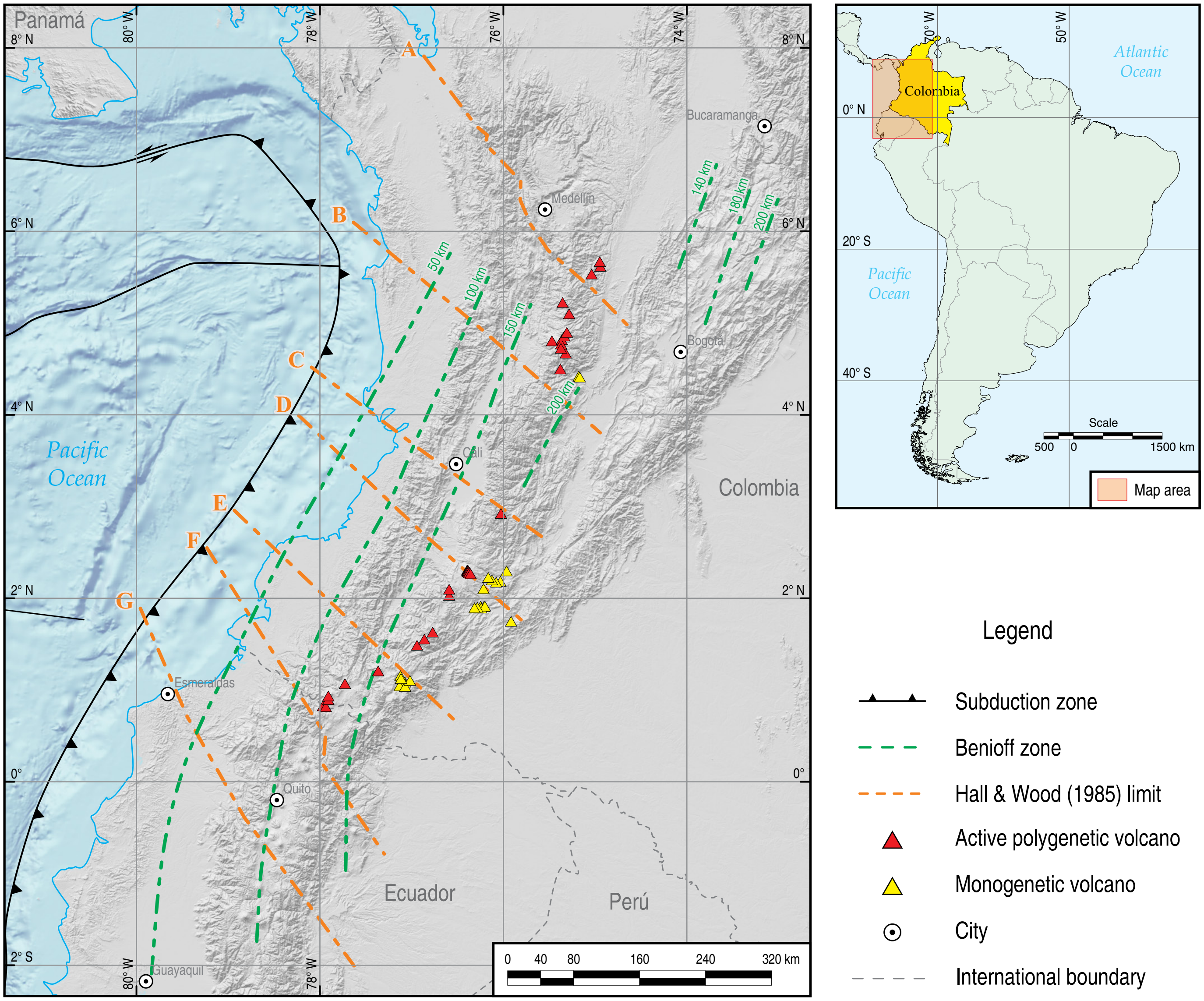


Figure 5. Tectonic segmentation of the northern Andes (boundaries after Hall & Wood, 1985; modified from Ortiz, 2018). Boundaries: (A) Cañasgordas; (B) Cartago; (C) Huila; (D) Puracé; (E) Guairapungo; (F) Río Mira; (G) Pastaza–Esmeraldas. The shape of the subducted oceanic plate is shown by green contours in kilometers, based on Pennington (1981)

the east of the segment and 35 km from the Galeras Volcano (Figure 6).

Lavas from these volcanoes are classified as two–pyroxene andesites and dacites with mineralogical associations of (1) plagioclase (Pg), orthopyroxene (Opx), clinopyroxene (Cpx), ± olivine (Ol), and oxides (Ox) and (2) quartz (Qz), Pg, amphibole (Am), biotite (Bi), and Ox. Evidence of fractional crystallization and magma mixing are common in their products. Geochemically, the lavas correspond to medium–K calc–alkaline andesites, dacites, and rhyolites (Figure 7a). The REE multielement diagram (Figure 7b) shows parallel patterns, with marked enrichment in LREE and depletions in HREE, especially in the samples of the Azufral Volcano. Negative Pr and Eu anomalies are observed for the Galeras samples. In the discriminatory diagram of adakitic and calc–alkaline rocks (Figure 8) proposed by Defant & Drummond (1990), the younger rocks of Azufral Volcano plot in the field of adakites.

4.1.1. Chiles–Cerro Negro Volcanic Complex

The Colombo–Ecuadorian border line passes through the summit of the Chiles–Cerro Negro Volcanic Complex (85 km SW from Pasto–Nariño). This complex consists of two adjacent volcanoes, Cerro Negro and Chiles, as well as a dacitic dome aligned with the WNW–ESE–oriented Chiles Fault (Figure 9). These volcanoes are classified as active stratovolcanoes (Bernard & Andrade, 2011; Cortés & Calvache, 1997; Sierra, 2015), and due to their proximity, they are considered to be fed by the same magmatic system (Organización Latinoamericana de Energía & Geotérmica Italiana, 1982). The structures are developed on pyroxene,

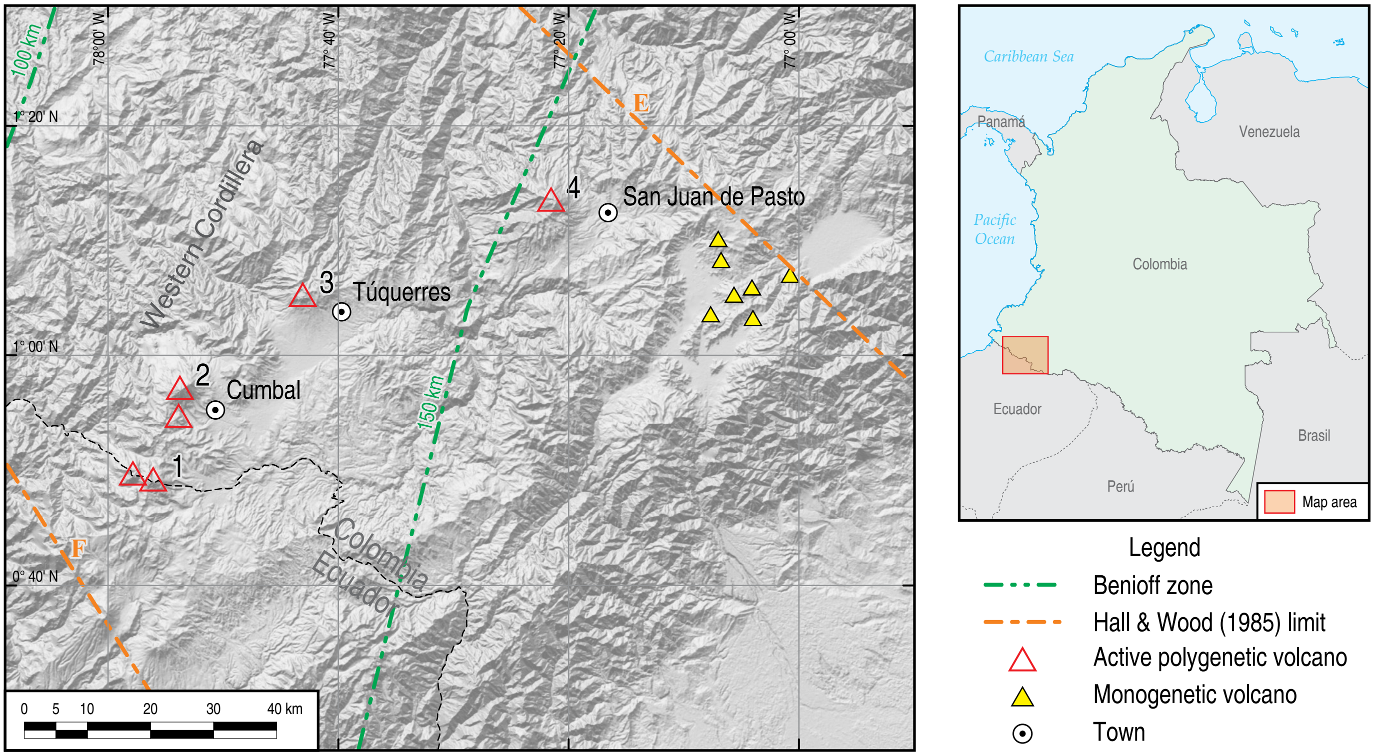


Figure 6. Volcanic structures that make up the southern volcanic segment: (1) Chiles–Cerro Negro Volcanic Complex, (2) Cumbal Volcanic Complex, (3) Azufral Volcano, (4) Galeras Volcanic Complex.

olivine, and hornblende lavas dating from 4.8 Ma (Instituto Colombiano de Energía Eléctrica (ICEL), 1983; Ramírez, 1982).

The Chiles Volcano displays an amphitheater morphology due to a flank collapse. Its activity, which is predominantly effusive, has produced thick deposits of lava flows (Cortés & Calvache, 1997) with ages between 0.5 and 0.05 Ma (Organización Latinoamericana de Energía & Geotérmica Italiana, 1982). Debris avalanche deposits associated with the collapse of the structure are exposed in the northern sector of the volcano. Ramírez (1982) reported a maar–type crater to the south, while Telenchana (2017) reported domes and small explosion craters in the high parts of the cone.

The Cerro Negro Volcano, also known as the Cerro Negro de Mayasquer or Cerro La Oreja (Arteaga, 1910; Karsten, 1886), consists of two superimposed structures with a horseshoe–shaped crater open to the west due to a flank collapse of the younger structure. Organización Latinoamericana de Energía & Geotérmica Italiana (1982) reported ages of 1.4 Ma for the oldest structure and 0.04 Ma for the youngest. Its products include ignimbrite, lava flows, scoria flows, and debris avalanches associated with the collapse of the flank (Cortés & Calvache, 1997). Organización Latinoamericana de Energía & Geotérmica Italiana (1982) indicates recent minor phreatic to phreatomagmatic activity for the Cerro Negro and Chiles Volcanoes.

The volcanic complex features significant sulfur deposits (Torres, 1982). Additionally, it is a target for binational geothermal exploration (Comisión Económica para América Latina y el Caribe (CEPAL), 2000).

The analysis of historical records suggests that the volcanic complex had minor eruptive activity in historical epochs. The word "Chiles" means "shines frequently" (Instituto Histórico del Perú, 1906), and in the second half of the 19th century, between 1860 and 1869, the Chiles Volcano showed intense fumarolic activity, which could have been associated with minor eruptive events on the southern flank. In the same period, incipient hydrothermal and fumarolic manifestations were reported inside the amphitheater of the Cerro Negro Volcano and possible eruptive activity towards the beginning of the 20th century, while the fumarolic activity in Chiles disappeared (Monsalve & Laverde, 2016). In turn, Santamaría et al. (2017) analyzed ash deposits in a peat bog between the two volcanoes and identified 12 layers of ash with ages between 5780 ± 30 years BP and 200 ± 30 y BP, although the layers were not attributed to the activity of these volcanoes. Since July 2013, an increase in seismicity has been evident, which is associated with the reactivation of the volcanic complex (SGC, https://www.sgc.gov.co/Noticias/Paginas/Boletines-mensuales.aspx; Torres et al., 2015; Sierra, 2015).

4.1.2. Cumbal Volcanic Complex

Located 73 km SW of Pasto, this complex consists of two adjacent active polygenic volcanoes: the Mundo Nuevo Volcano,

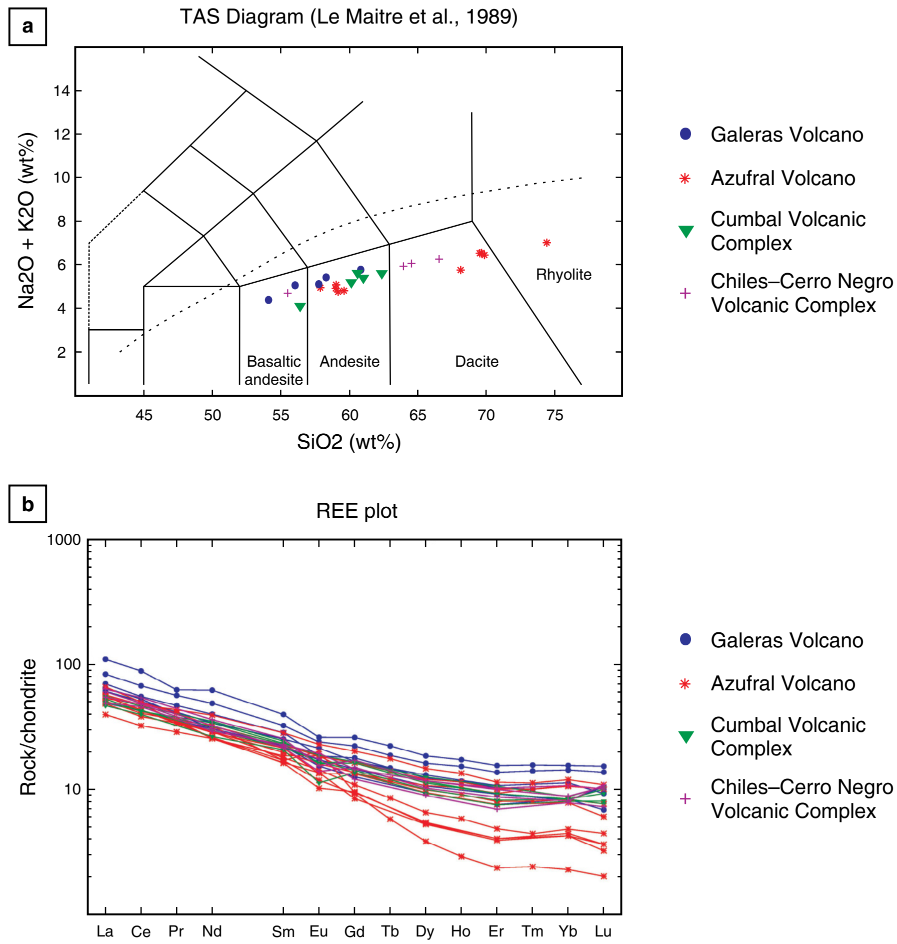


Figure 7. (a) IUGS TAS (total alkali silica) diagram for the classification of volcanic rocks (Le Maitre et al., 1989), with representative samples from the southern volcanic segment. **(b)** REE diagram normalized to the chondrite data from Sun & McDonough (1989). Data from (Droux & Delaloye, 1996; Marín–Cerón, 2007). The diagrams were created using PINGU tool (Petrological INput–Graphical oUtput) from Cortés & Palma (2018).

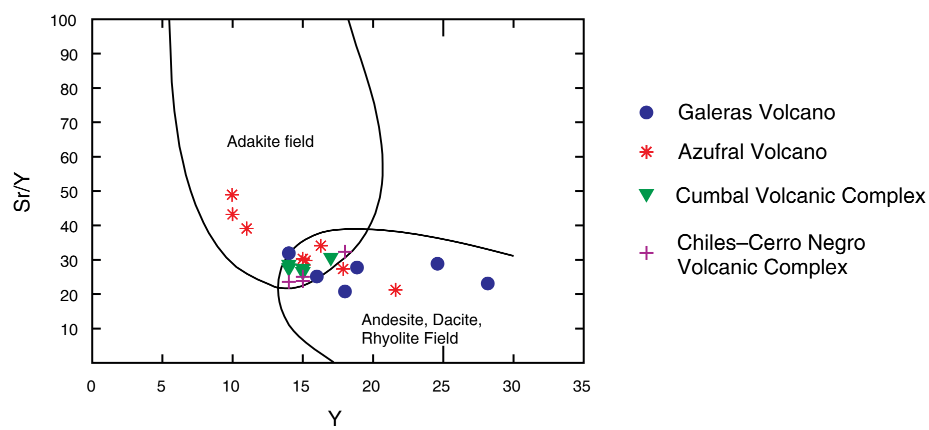


Figure 8. Adakite discriminatory diagrams (Defant & Drummond, 1990). The samples from Azufral Volcano plot from the normal calc–alkaline field to the adakite field, whereas those of the Galeras, Cumbal, and Chiles–Cerro Negro Volcanic Complexes are predominantly in the normal calc–alkaline field. The data are shown in Figure 7. The graph was created with the igneous petrological tool (IGPET).

Figure 9. Panoramic view of the Chiles–Cerro Negro Volcanic Complex in 2008. Note the partial collapse of the Chiles structure and the two structures that make up the Cerro Negro Volcano. Source: SGC, https://www2.sgc.gov.co/sgc/volcanes/VolcanCerroNegro/Paginas/Galeria-de-imagenes.aspx

with a crater 200 m in diameter, and the Cumbal Volcano, with a crater (known as La Plazuela) 250 m in diameter and open to the SE, as well as several cones and adventitious craters (Punta Vieja, Nieve Vieja, and Cerro La Teta) (Figure 10) aligned in a NNE–SSW orientation with the Cauca–Patía Fault (Méndez et al., 2014; Monsalve & Méndez, 1988; Ramírez, 1982). This complex developed on the products of previous stages of volcanism initiated approximately 5.1 ± 0.4 Ma with the formation of the Colimba Caldera (Organización Latinoamericana de Energía & Geotérmica Italiana, 1982).

The activity of the complex is mainly effusive, and the dominant products are lava flows approximately 9 km long, although pyroclastic deposits corresponding to scoria flows and ballistic projectiles occur in smaller proportions (Gorman, 1997; Méndez et al., 2014). An age of 0.2 Ma was reported by Ramírez (1982) and Gorman (1997) for lavas from the most recent stage of the volcanic complex. An age of 3800 years for pyroclastic surge deposits was indicated by Instituto Colombiano de Energía Eléctrica (1983).

The petrographic and geochemical similarities of the products suggest that the system is fed by a common magma chamber, where processes of magmatic differentiation occur (Gorman, 1997; Monsalve & Bechon, 1993).

Hantke & Parodi (1966) reported eruptive activity in December 1877, but no precise description was provided although the area was inhabited at this time. They also reported explosive activity on 20–21 December 1926; however, the versions on this eruption could have arisen as a result of the recognition of the complex by the volcanologist Friedlaender (1927) because an earthquake that destroyed the town of Cumbal in 1923 was erroneously attributed to an eruption of the Cumbal Volcano. von Humboldt (1800) mentioned fumarolic activity at the beginning of the 19th century, and this activity was captured in a drawing in 1853 (Figure 11) and in 1927 by Friedlaender (1927). Currently, the Cumbal and Mundo Nuevo Volcanoes continue to display substantial fumarolic activity.

4.1.3. Azufral Volcano

Also known as Túquerres Volcano or formerly as Chaitán (Rosero, 2010), the Azufral Volcano is located 50 km SW of Pasto. It is a structure with a 2 × 3 km crater containing 10 domes (Fontaine, 1994; Fontaine & Stix, 1993) and an emerald–green lake (Figure 12). The volcano developed on ancient structures that generated andesitic lava flows dated to 0.58 Ma (Bechon & Monsalve, 1991) and 0.4 Ma (Ramírez 1982), as well as large ignimbrite deposits, indicating prolonged magmatic activity related to a possible N–S migration of volcanism (Fontaine, 1994) along the Cauca–Patía Fault.

Six units represent the eruptive history of the Azufral Volcano between 17 500 and 280 y BP (Table 2). These units are interpreted by Williams et al. (2017) to represent short periods of explosive activity that generated pyroclastic deposits and debris avalanches and were separated by prolonged quiescent periods. The deposits generated by the eruptions are block and ash flows associated with the collapse and explosion of domes,

Figure 10. Panoramic view of the Cumbal Volcanic Complex in 2013 with its corresponding volcanic structures. Modified from Méndez et al. (2014).

Table 2. Eruptive units defined in the Azufral Volcano for the last 20 000 years, modified from Cortés et al. (2009)

Age (years BP)	Stratigraphic unit			
	Betancur & Correa–Tamayo (1992)	Fontaine (1994)	Torres et al. (2001)	Torres et al. (2003)
280	MA2: AC4		Laguna Verde	Laguna Verde
2880 ± 200	MA9	CP7		La Calera
3470 ± 60	MA6: AS1, AF9	CP6	El Carrizo	
ca. 3600	MA5: AF6	L2, CP5	El Espino	El Espino
	MA4: AC2, AC3, AF5	RT2, RT3, CP4	La Cortadera	Guaicés
ca. 4000	MA3: AF4, AC1	RT1, CP3	La Calera	Vervena
	MA2: AF3			La Ciénaga
17 970 ± 190	MA1: AF1, AF2	CP2	Túquerres	Santander de Valencia

ash and pumice flows, and pyroclastic surges (Castilla et al., 2017; Cortés et al., 2001; Organización Latinoamericana de Energía & Geotérmica Italiana, 1982; Torres et al., 2001, 2003) generated by phreatomagmatic activity that left explosion craters inside the main crater (Ramírez, 1982; Organización Latinoamericana de Energía & Geotérmica Italiana, 1982). Pumice fall deposits, reported by Betancur & Correa–Martínez (1992), Fontaine (1994), and Ramírez (1982), are interpreted by Torres

Figure 11. Painting by Manuel María Paz, January 1853: "Fumarolic activity in the Chiles and Cumbal Volcanoes". Source: Gutiérrez de Alba (1875). The Cumbal Volcano is positioned on the right side of the drawing. The Chiles Volcano (left), as designated by the artist, possibly corresponds to the Mundo Nuevo Volcano. A comparison of the drawing with Figure 10 suggests that it depicts the Cumbal Volcanic Complex from a slightly more southern perspective than the Figure 10 photograph.

et al. (2001) as deposits formed by pyroclastic surges. Some deposits, classified as block and ash flows generated from the domes, have been reinterpreted by Williams et al. (2017) as debris avalanches.

Azufral is considered an active volcano based on the Holocene eruptive record, the presence of thermal springs, fumarolic activity in the youngest dome (Mallama), and hydrothermal eruptions described since the nineteenth century by Boussingault in 1831 (Boussingault, 1985), André (1884), and von Humboldt (1800), who referred to the volcano as a solfatara. Recently, this type of activity was recorded in July 2009 (Gómez & Ponce, 2009), May 2016, and June 2017, with small sulfur flow deposits that extended up to 10 m in the Laguna Verde (Figure 13).

4.1.4. Galeras Volcanic Complex

Described by chronicles such as the Volcano of Pasto (Espinosa–Baquero, 2011, 2012), the Galeras Volcanic Complex is located 9 km from Pasto in the Cauca–Patía Valley. It corresponds to remnants of structures that represent successive stages of construction and destruction of volcanic edifices over approximately one million years (Calvache, 1995; Ramírez, 1982). The most recent stage, known as the Galeras stage, started approximately 5000 years ago (Calvache, 1990; Calvache et al., 1997), during which the Galeras Volcano sensu stricto (Figure 14), a monogenetic scoria cone located on the south flank of the complex named La Guaca and a set of fissure lavas to the north and northeast, were built. The Galeras Volcanic Complex is controlled by the Romeral and Buesaco Faults and the Guairapungo lineament, which marks the northern boundary of the southern segment of active Colombian volcanism (Hall & Wood, 1985).

The Galeras Volcano is built within amphitheater structures formed by collapses in the western sector of pre–existing volcanic structures 12 000 to 5000 years ago (Calvache, 1995). Galeras is a polygenetic cone 300 m high built at the base of the amphitheater; it has a crater 320 m in diameter

Figure 12. Panoramic view from the W of the Azufral Volcano; the crater with the dome complex and the Laguna Verde are visible. Source: SGC, https://www2.sgc.gov.co/sgc/volcanes/VolcanAzufral/Paginas/imagenes-Volcan-Azufral.aspx.

with varying morphology and depth since its reactivation in 1988 (Ordóñez & Cepeda, 1997). The cone features several secondary craters and fumarolic fields with emissions of volcanic gases and water vapor.

Six eruptive members for the Galeras stage were defined by Calvache (1990) named 4500, 4000, 2900, 2300, 1100, and 1866 from oldest to youngest, which are mainly associated with vulcanian activity. Deposits from this activity correspond to block and ash flows from the destruction of domes, scoria flows, hydrothermalized lithic flows that represent phreatic activity phases, pyroclastic surges, pyroclastic falls (of ash, lapilli, and ballistic projectiles), and lava flows, some of which have been erupted in historical times (Banks et al., 1997; Calvache, 1990; Calvache et al., 1997; Ramírez, 1975). Secondary lahars are also found within the stratigraphic sequence of this volcano.

Galeras is considered the most active volcano in Colombia and has experienced almost continuous eruptions since pre–Hispanic times, as inferred from the text of the chronicler Cieza de León (1922) when passing through Pasto to the south in 1547:

> "*... Farther ahead is a high mountain range; at its summit, there is a volcano from which smoke sometimes comes out, and in past times (as the natives say), it burst once and threw out a great amount of rocks ...*"

The historical activity was described and compiled by naturalists, chroniclers, and historians. More recent publications have collected, complemented, and interpreted this information (i.e., Cepeda, 1995; Espinosa–Baquero, 1988, 2011, 2012; Ramírez, 1975).

Historical reports describe hundreds of eruptive events, including small ash emissions that indicate almost continuous volcanic activity over a long period of time, interrupted by short "quiescent periods" of months to a few years, with the longest lasting between 35 and 40 years (Servicio Geológico Colombiano, 2015). This activity has mainly been of vulcanian type,

Figure 13. Interior activity of the Azufral Volcano. **(a)** Note the intense fumarolic activity in the most recent dome (Mallama) at the end of the 19th century according to Édouard Riou's engraving *The green lagoon, crater of the sulfur volcano*, which is based on a drawing by Édouard Francois André in 1870 (André, 1884; Acevedo–Latorre, 2001) **(b)** Interior hydrothermal eruptive activity in the crater of the Azufral Volcano in July 2009. **(c)** Deposits related to similar activity in May 2016. Photographs (b) and (c) taken from the SGC database, Observatorio Vulcanológico y Sismológico de Pasto.

producing ash emissions and ballistic projectiles (bombs and blocks), followed by the generation of shock waves and phases with lava emissions and small pyroclastic flows, as evidenced on the cover of the magazine *Ilustración Nariñense* in 1940 (Espinosa–Baquero, 2011). Table 3 summarizes the historical activity of this volcano.

In 1988, after a quiescent period of 38 years, the Galeras Volcano showed signs of reactivation with an increase in fu-

Figure 14. Aerial view of the active cone of the Galeras Volcano in 2004, which developed inside the remnants of the volcanic complex that form an amphitheater structure open to the W. Source: SGC database, Observatorio Vulcanológico y Sismológico de Pasto, https://www2.sgc.gov.co/sgc/volcanes/VolcanGaleras/Paginas/fotos.aspx

marolic activity (Monsalve & Mosquera, 1988), a gradual increase in seismicity, minor ash emissions, and incandescence in the main crater (Cepeda et al., 1989). This reactivation activity evolved towards a vulcanian eruptive style (Figure 15), which has persisted to the present day and has been characterized by the extrusion and destruction of intracrater domes leading to moderate and intermittent explosions followed by shock waves and the ejection of ash and ballistic projectiles. The current activity has featured 28 eruptive phases, numerous minor ash emissions, and continuous gas emissions (Table 3), which have been generally unnoticed by the surrounding population but have been recorded by the monitoring equipment of the SGC, Observatorio Vulcanológico y Sismológico de Pasto (https://www.sgc.gov.co/volcanes). Additionally, small mudflows have occurred, similar to that in October 2004, which descended through the Azufral River valley and reached distances greater than 9 km (Pulgarín, 2005). Deposits from these eruptions are preserved only in the upper part of the structure because most of the material, especially ash, is removed by rain and wind to remote areas.

4.2. Central Volcanic Segment

The central volcanic segment is located in the southern part of the Central Cordillera between limits E (Guairapungo) and D (Puracé) according to Hall & Wood (1985) (Figure 5). The Nevado del Huila Volcano marks limit C (Hall & Wood, 1985) corresponding to the Buenaventura–La Plata lineament described by Ujueta (2001). The volcanoes in this segment are controlled mainly by the Silvia–Pijao Fault (Figure 3). This segment consists of three groups of active volcanoes with specific characteristics (Figure 16), separated by small gaps with signs of older volcanism (Ceballos et al., 1994; Flórez, 2003).

The volcanic front is located 270 to 280 km from the trench. These volcanoes mostly developed inside ancient calderas, and

Table 3. Summary of the historical activity of the Galeras Volcano. Modified from Servicio Geológico Colombiano (2015). Products: (A) Ash; (B) blocks or bombs; (I) incandescence; (Sw) shock wave; (Lh) lahar; (M) mud; (Exp) explosion; (Dm) dome; (Fm) fumarole; (Erp) eruption; (Pf) pyroclastic flow; (Sm) smoke; (S) sulfur; (Eq) earthquake; (Rmb) rumbling noises.

Activity Date		Products	VEI	Column height (km)	Volume (m^3)
Year	Day/Month				
2012	During the year	Minor ash emissions			
2010	25/08, 02/01.	A/A, B, I			3 560 000
2009	20/11, 30/10, 8–7/06, 1–4–5/05, 29–15/04, 13/03, 14–20/02.	A, B			6 570 000
2008	17/01, 8–12/07.	A, B		1 to 10	870 000
2006	07/12, 06/08.	A			390 000
2005	27/12, 24/11.	A			700 000
2004	21/11, 20–21–24–25–26/10, 1–3–4–7–23–24/09, 11–12/08, 16, 21, 28/07.	Sw, A, B, Lh. A continuous emission from El Pinta Crater 07/28–09/8	1	1 to 10	2 400 000
2002	02/06	A			
1993	7/06, 4–13/04, 23/03, 14/01.	Exp, B, A	1	2 to 10	2 500 000
1992	16/07	Exp, Dm, B, A	1	4 to 6	277 000
1991		Dm extrusion			
1990	02/08	B (interior of the phreatic crater)			
1989	4–5–6–7–9/05, 5/04, 26/03, 19/02.	A, A continuous emission from El Pinta, phreatic Exp		3 to 3.5	1 200 000
1950	12/01, and February–September.	A/Fm			
1949		Doubtful			
1947		Doubtful			
1944		A, photograph			
1942		A, photograph			
1937		Erp			
1936	27/08, 9/02	A, Pf, B, Exp		7 to 12	
1935	9	A			
1934	14, 10/12.	Erp, A			
1933	1, 3, 4/01.	Sm, S smell			
1932	4–10–19–20–23/10, 3–4–5–6–8–9/11, 5–8–10–15/10, 1–30/09, 8–18/05, 28/04, 7–8–22/03, 8–10–16–21–22/02, 23/01.	Black Sm Erp, gases			
1931	14–19–24–28/11, 17–19–24–28/07, 4–24–25/06/, 30/05, 20/04.	Sm Column, A, Exp		4	
1930	04/01	Exp			
1927	01/06, 4–8/05, 12–13–21/04, 2–6–15/02, 16/01.	Exp, A, Erp, Sm		Great height	
1926	11/14, 10/28, 09/29–28–27–22, 07/10, 05/1, 04/15–9–6–3, 03/27–26–21–20–17–11–9–3, 02/11–10–1, 01/ 5.	Magnificent erp, Eq, Sm col, Exp, noises, A, I			
1925	27–30–31/12/, 1–2–3–6–13–15–16–17–21–22/11, 1–3–27–30/10, 1–3–4–7–8–11–13–14–15–16–17/09, 2–4–8/08, 1–2–3–8–10–13/07, 4–6–7–8–9–29/06, 9–14–15–18–19–23–25–26/05, 25/03, 9–15/02.	A, B, Erp, Sm, Exp, A, B, I, noises, Eq		3	
1924	12–13–14–15–16–18–19/12	Vapor col, black col, Dm, Exp, A, Sm col		0.5	
1923	12–14/08	A			
1918		Low A emission			
1905	19/04	Erp			
1889–1891		Erp col (*A?), Lh			
1887	3/07	Exp, I			

Table 3. Summary of the historical activity of the Galeras Volcano. Modified from Servicio Geológico Colombiano (2015). Products: (A) Ash; (B) blocks or bombs; (I) incandescence; (Sw) shock wave; (Lh) lahar; (M) mud; (Exp) explosion; (Dm) dome; (Fm) fumarole; (Erp) eruption; (Pf) pyroclastic flow; (Sm) smoke; (S) sulfur; (Eq) earthquake; (Rmb) rumbling noises (*continued*).

Activity Date		Products	VEI	Column height (km)	Volume (m^3)
Year	Day/Month				
1869–1887		Minor erp			
1869	9/07, 9–15/06, 27/03.	A, M, Exp, B		8.7	
1868					
1867		Activity			
1866		Lava, rocky basalts, erp col, (*A?), Pf? Lh			
1865	02/10	Erp col, A		5.7	
1863–1865		Minor erp			
1856		Lava, rocky basalts, erp col (*A?) Pf? Lh			
1836		Minor erp			
1834	01/03	Exp, I, Eq			
1832	18/12	A			
1831	15/06	Fumarole 235°, B			
1830		Minor erp, barely noticeable			
1829		Minor erp, barely noticeable			
1824	24/10	Low–intensity erp			
1823	24/06	B, M, A			
1801	23/12	A			
1797	1	Sm col			
1796	11–12	Sm col, minor exp			
1760		I overview from Pasto			
1756		Dm exp, A, lapilli, B			
1754–1756		Exp period, A, B, S			
1741					
1736					
1727		Erp col (*A?)			
1717		Exp, A, lapilli, continuous activity, slag, lava cone of 146 m			
1710		A			
1696		Eq, erp col (*A?)			
1687–1696		Frequent erp with Eq			
1641–1643		Expl, B, Pf			
1616	06/04	Sm, A and S, B, M, Pf			
1590	12/07	B, M, A		0.078	
1580	12/07	Boiling water, B, spilled A, M, Pf, B			
1754		Volcano that always spews fire, B, noises			
1559–1560		Fire–Sm			
1535		Exp			

Source: Data from Monsalve et al. (2015a).

Figure 15. Volcanic eruptive activity on 2 January 2010, at 10:12 pm. Note the eruptive column and the fires in the upper parts of the volcano caused by the fall of ballistic projectiles. Source: SGC database, Observatorio Vulcanológico y Sismológico de Pasto, photograph courtesy of Luis PONCE M.

some have not been studied due to their isolated locations and difficult access. Towards the eastern part of the segment, the "Alkaline Province" named by Kroonenberg et al. (1982, 1987), is located; it consists of monogenetic volcanic fields (see Monsalve et al., 2020).

To the south of the Nevado del Huila Volcano, Pennington (1981) highlighted the absence of intermediate seismicity, while Idárraga–García et al. (2016) indicated a strip with no seismicity between this volcano and the Sotará Volcano.

Petrographically, the products of the volcanoes in this segment correspond to two–pyroxene andesites, amphibole andesites, and dacites, with mineralogical associations of Pg, Opx, Cpx ± Ol, and Ox; Pg, Opx, Cpx ± An, and Ox; and Pg, Cpx, An ± Bt ± Qz ± Ol, and Ox. Evidence of fractional crystallization and magma mixing is common in these volcanic products. Geochemically, these products correspond to basaltic andesites, andesites, and dacites; with medium–K calc–alkaline affinity, except for the samples of the Coconucos Volcanic Chain, which are high–K andesites (Figure 17a; Droux & Delaloye, 1996; Monsalve et al., 2012; Ramírez, 1982). The REE multielement diagram (Figure 17b) shows that the volcanoes in the central volcanic segment exhibit parallel patterns along with marked enrichment in LREE and depletion in HREE, as well as either a lack of anomalies or positive Eu anomalies, especially in the Doña Juana Volcano samples. The discrimination diagrams for adakitic and calc–alkaline rocks (Figure 18) by Defant & Drummond (1990) show that most of the lavas in this segment plot transitionally between the calc–alkaline field and adakite field (Monsalve et al., 2011a). The adakite signature is more evident in recent samples from the Nevado del Huila Volcano (Figure 18). This trend has also been noted by Correa–Tamayo (2009), Correa–Tamayo & Ancochea (2015a), and Monsalve et al. (2015b).

4.2.1. Doña Juana Volcanic Complex

This complex is located in the southern sector of the Central Cordillera in the region of the Macizo Colombiano, within the limit of the Departments of Cauca, Nariño, and Putumayo and 51 km NE of San Juan de Pasto city (Figures 1, 16). It consists of the remnants of three superimposed volcanic edifices and two satellite structures (Figure 19) developed in three eruptive periods, with the most recent corresponding to the Doña Juana

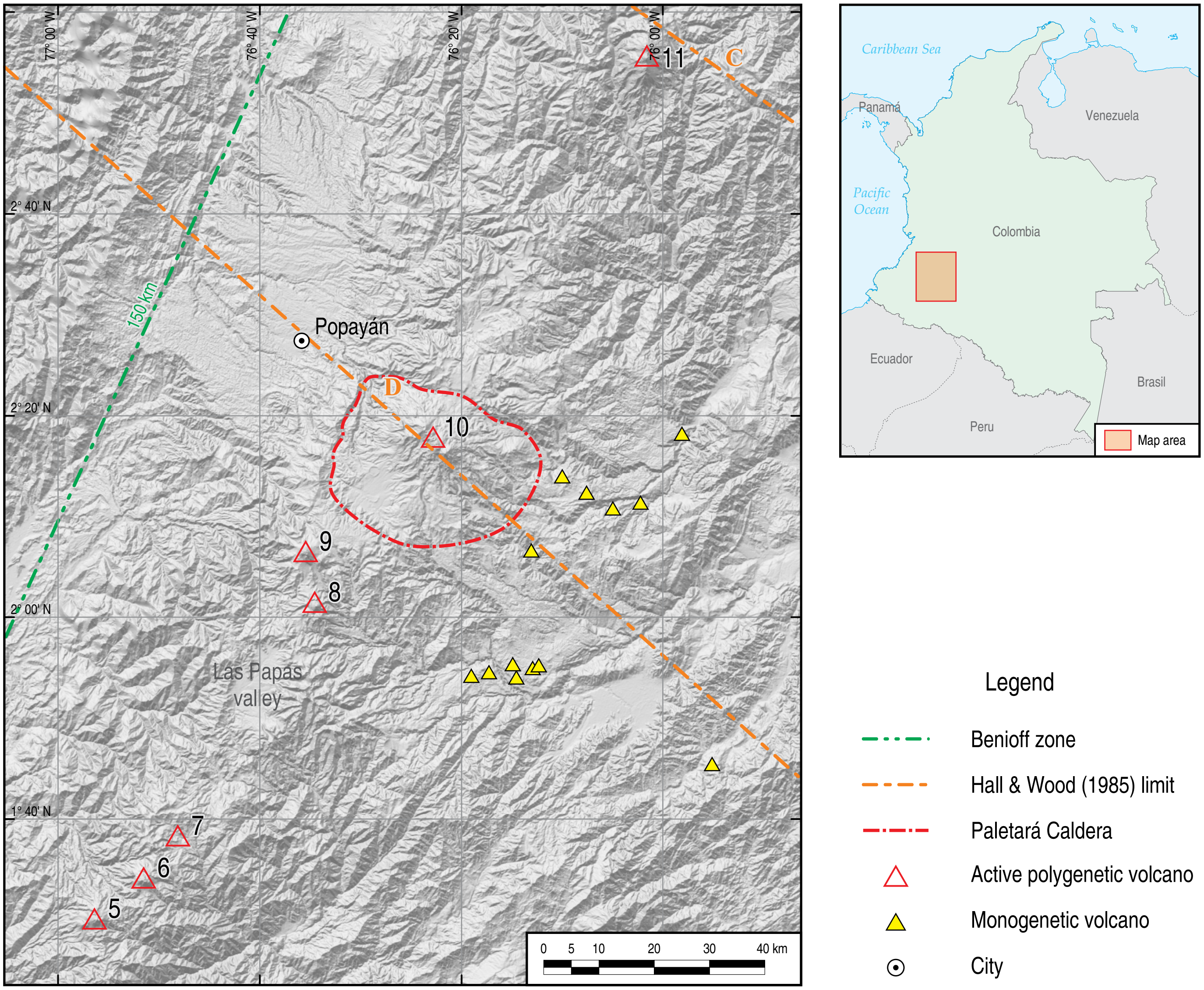


Figure 16. Location of the central volcanic segment in Colombia: (5) Doña Juana Volcanic Complex, (6) Ánimas Volcano, (7) Petacas Volcano, (8) Sucubún Volcano, (9) Sotará Volcanic Complex, (10) Coconucos Volcanic Chain, (11) Nevado del Huila Volcanic Complex.

Volcano sensu stricto (Navarro et al., 2009; Pardo et al., 2016; Pulgarín et al., 2008; Steimle, 1989,). This complex is bounded by the Silvia–Pijao–El Tablón Fault and San Jerónimo Fault (Figure 3). Ramírez (1982) assigned an age of 2.3 Ma to the oldest products; Murcia & Pichler (1987) reported an age of 1.5 Ma, which was obtained from an ignimbrite deposit, while Pardo et al. (2016) determined an age of 1.1 Ma.

The deposits associated with the activity of the Doña Juana Volcanic Complex are lava flows, pyroclastic density currents, pyroclastic falls, pumice flows, domes, block and ash flows, and secondary lahars.

The evolutionary history of the complex and its products was initially described in terms of eruptive units (Navarro et al., 2009; Pulgarín et al., 2008). In more recent studies, the complex has been described in terms of lithostratigraphic units (Pardo et al., 2016, 2019), and 10 eruptions of the Doña Juana Volcano have been identified in the last 10 000 years. These eruptions left a geological record characterized by the extrusion and destruction of domes, both by gravitational collapse and by explosion, thus generating block and ash flow deposits, surges, and secondary lahars (Table 4).

Ceramic fragments in a paleosol and in a block and ash flow deposit that have been dated to 1710 ± 30 y BP and 610 ± 30 y BP, respectively (Pardo et al., 2016), show the effect of the volcano on the area of influence in pre–Hispanic times.

The 1897–1899 eruptive period of the Doña Juana Volcano marked the most explosive eruptive activity in historical time in Colombia. Stories about this activity are documented by Eraso (1989), Espinosa–Baquero (2011), and Ramírez (1975). These authors described several violent eruptive phases during this period (Table 5), followed by earthquakes caused by the explosion and collapse of domes, which also generated pyroclastic

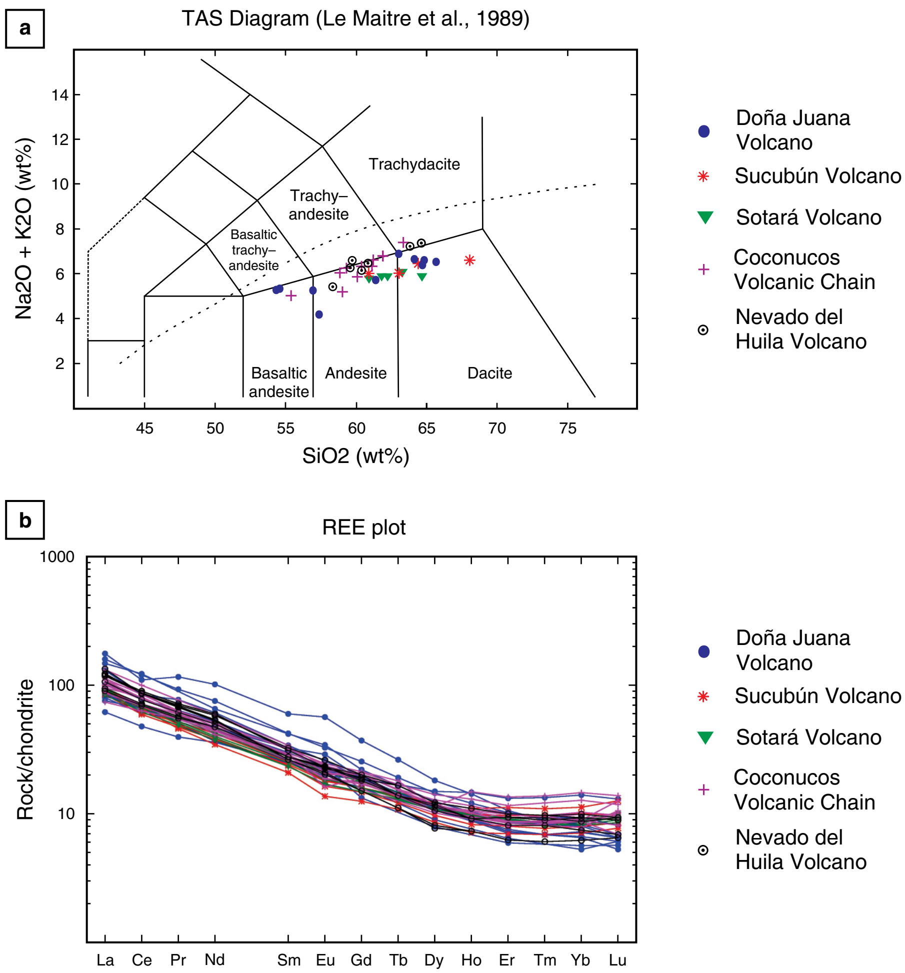


Figure 17. (a) IUGS TAS diagram for the classification of volcanic rocks (Le Maitre et al., 1989), with representative samples from the central volcanic segment. **(b)** REE diagram normalized to the chondrite data of Sun & McDonough (1989). Data from Correa–Tamayo (2009), Droux & Delaloye (1996), Marín–Cerón (2007), and Pulgarín et al. (2010). The diagrams were created using the Cortés & Palma (2018) PINGU tool.

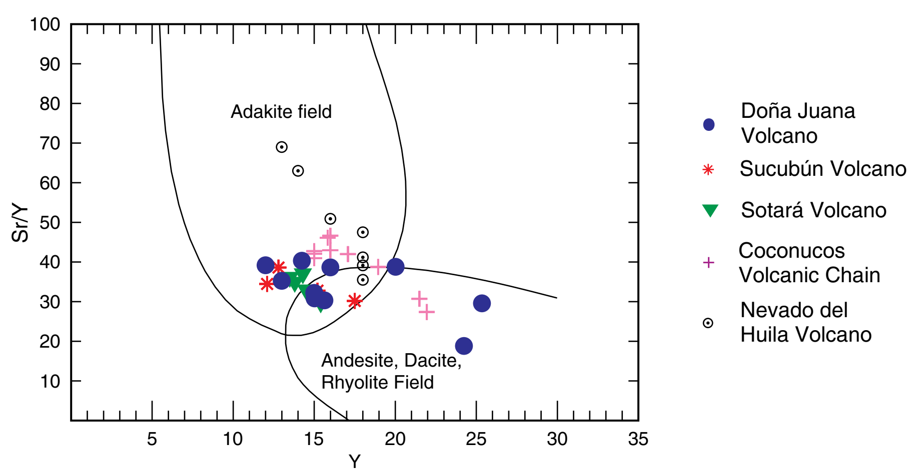


Figure 18. Adakite discrimination diagram (Defant & Drummond, 1990). Most volcanic samples plot in the adakite field. Data are shown in Figure 17.

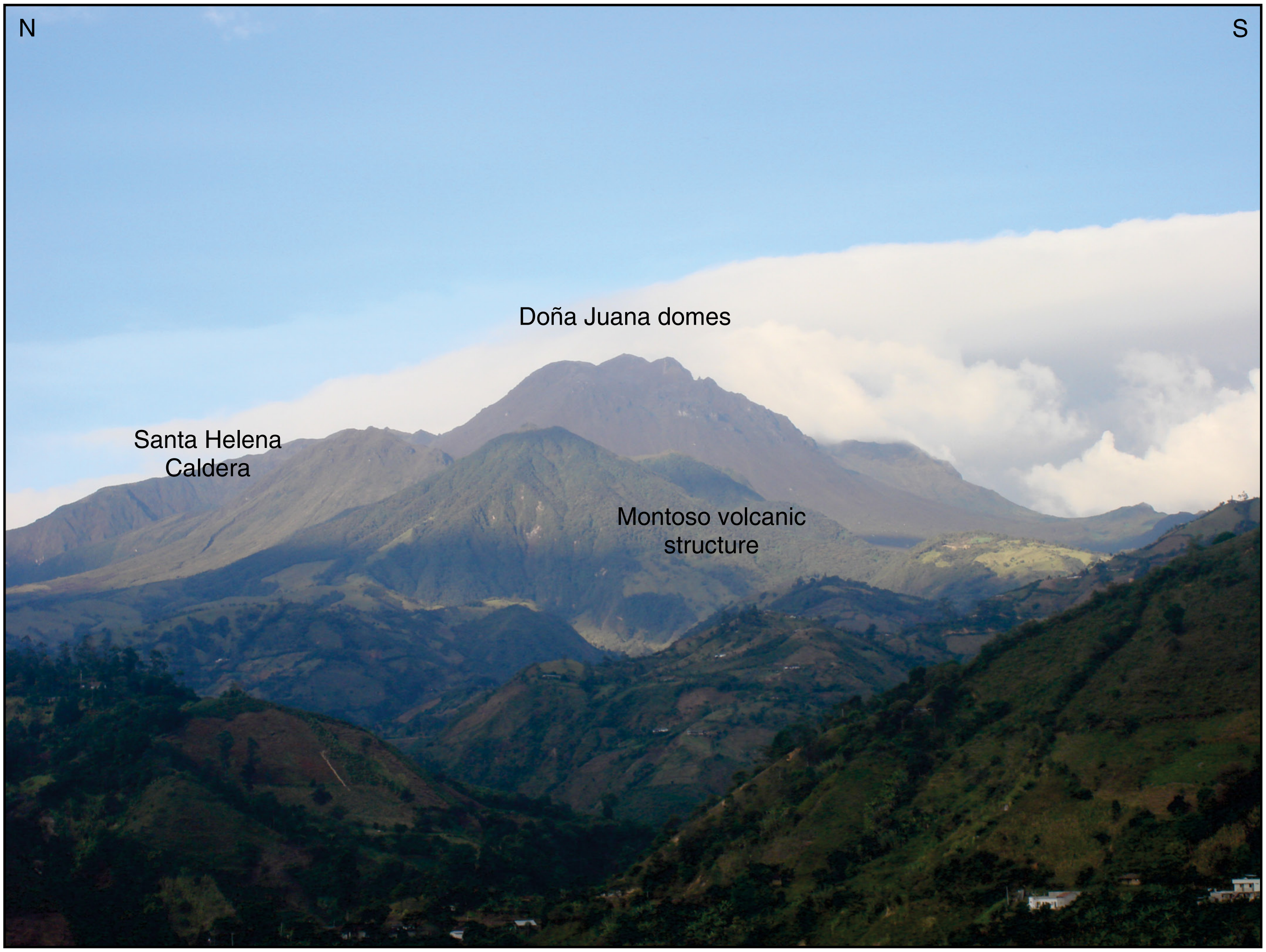


Figure 19. Overview of the Doña Juana Volcanic Complex in 2007, from the west. The background shows the current domes of the Doña Juana Volcano. Source: SGC database, Observatorio Vulcanológico y Sismológico de Popayán, https://www2.sgc.gov.co/sgc/volcanes/ComplejoVolcanicoDonaJuana/Paginas/imagenes.aspx

flows, ash falls, ballistic projectiles, and secondary lahars. The deposits left by this eruptive activity were identified during field work (Figure 20) and consist of block and ash flows, pumice flows, pyroclastic surges, and ballistic projectiles (Pardo et al., 2016; Pulgarín et al., 2008).

Hantke & Parodi (1966) reported the eruptive activity of the Doña Juana Volcano from 1897 to 1906 and described it as the formation and subsequent destruction of a dome in the "central cone". A new eruption was reported in 1936 (Espinosa–Baquero, 2011), although interviews with inhabitants and fieldwork in the area confirm that it was a mudflow generated from a natural dam in the Resina River that originates on the volcano (Pulgarín et al., 2008).

In addition to the historical eruptions, the thermal springs near the volcano documented by Royo y Gómez (1942b) and Organización Latinoamericana de Energía & Geotérmica Italiana (1982) and the seismic activity reported by the SGC–Observatorio Vulcanológico y Sismológico de Pasto provide evidence for the active state of the volcano. The last report of fumarolic activity in the summit domes was made by Steimle (1989).

4.2.2. Ánimas Volcano

This volcano is located 11 km NE of the Doña Juana Volcano and 60 km NE of Pasto (Figures 1, 16). Due to social factors, this volcano has not been the subject of direct studies; therefore, the limited knowledge we have comes from photogeological interpretations (i.e., Ceballos et al., 1994) and studies of the Doña Juana Volcano (Pardo et al., 2016; Pulgarín et al., 2008) because some of the main streams that form the Mayo River originate on these two volcanoes, thus allowing the identification and interpretation of some deposits associated with the Ánimas Volcano.

Morphologically, the most recent stage of the volcano corresponds to a pyroclastic ring–dome complex (Figure 21). Photogeological observations show that the Cerro de las Ánimas consists of a set of domes that have a diameter greater

Table 4. Comparison of the nomenclature used in different works to describe the eruptive activity of the Doña Juana Volcano.

Pulgarín et al. (2008)	Pardo et al. (2016)
Eruptive units	**Litho–stratigraphic units**
Cerro Montoso	Litosoma Montoso
U.E. Ciénaga Alta – Alto Sano (CAS)	Pyroclastic fall deposit (ca s_2) from La Cruz Formation: Ciénaga Alta–Alto Sano (lcrcas) member
U.E. Las Ánimas (LAS)	Purgatorio tuffs
U.E. Caucanes Alto (CA)	Caicuanes (cai) Formation
U.E. Tajumbina (TAJ)	La Cruz Formation: Tajumbina (lcr$_{taj}$) member
U.E. El Salado (SAL)	
U.E. Las Mesas (LM)	Las Mesas (lm$_i$) Formation, lower member
U.E. Monolitos (MON)	Las Mesas (lm$_m$) Formation, intermediate member
U.E. Paramito (PAR)	
U.E. El Común (COM)	
U.E. Humadal (HMD)	Las Mesas (lm$_s$) Formation, upper member
U.E. El Carmelo (CAR)	
U.E. El Indio (EIN)	
U.E. Peñas Blancas (PB)	
U.E. Dantas (DAN)	Las Mesas Formation, NW from Doña Juana Volcanic Complex
U.E. La Plata (PLA)	La Plata (pla) tuff breccia
U.E. Briceño–Cabuyales (BC)	Río Mayo (rm$_i$) Formation, lower member
U.E. El Chilcal (CHI)	Río Mayo (rm$_s$) Formation, upper member
U.E. Río Mayo (RM)	
U.E. La Cabaña (LAC)	La Cabaña (lac) Formation
Rellenos de paleocanal no diferenciados	La Vega (elv) epiclastics
U.E. La Vega Alta (LVA)	La Vega Alta (Iva) Formation
U.E. Puente Mayo–La Vega (PMV)	
Domo Este	Dome E–El Filo lithosome
Domo Norte	Dome NE; Ciénaga (cn$_i$) Formation, lower member
U.E. El Faldón (EFD)	Ciénaga (cn$_m$) Formation, intermediate member
U.E. Los Churos (CHU)	
U.E. Las Juntas (JNT)	
U.E. Ciénaga–El Placer (PLC)	Ciénaga (cn$_s$) Formation, upper member
U.E. Puente Los Churos–Tajumbina (PCT)	
U.E. La Vega Baja (LVB)	
U.E. Lahares de Molinos (MOL)	
Domo Sur	Central dome; El Silencio (si$_i$) Formation, lower member
U.E. El Pailón (EPL)	El Silencio (si$_m$) Formation, intermediate member
U.E. La Sofía (SOF)	
U.E. Lahares de Janacatú (JAN)	El Silencio (si$_s$) Formation, upper member
Lahar de 1936	

than 2.5 km and a well–preserved morphology, thus confirming its recent age. The domes also display secondary explosion craters, and some of them have short lava flows (Monsalve & Terraza, 1996).

Some deposits associated with this volcano are interlayered with deposits from the Doña Juana Volcano and correspond to welded ignimbrites, pumice flows, block and ash flows, and lahars (Pardo et al., 2016; Pulgarín et al., 2008), as well as an

Table 5. History of the Doña Juana Volcano eruptive activity between 1897 and 1899, as recorded in the diary of Mr. Luis MARTÍNEZ from the locality of Las Mesas.

Doña Juana Volcano eruptive activity between 1897 and 1899	Comment
1 November 1897, 9 a.m.	The Doña Juana hill burst
6–7 September 1898	The Doña Juana Volcano erupted violently
20 April 1899, 5 p.m.	The Doña Juana Volcano erupted strongly, and 31 inhabitants perished.
5 May 1899	Another eruption of lava and rocks
28 May 1899, 7 a.m.	The volcano erupted again, and 5 inhabitants perished.
13 November 1899, 2 p.m.	The great eruption of Doña Juana; 10 inhabitants perished. The population was evacuated.

Source: Data from Eraso (1989).

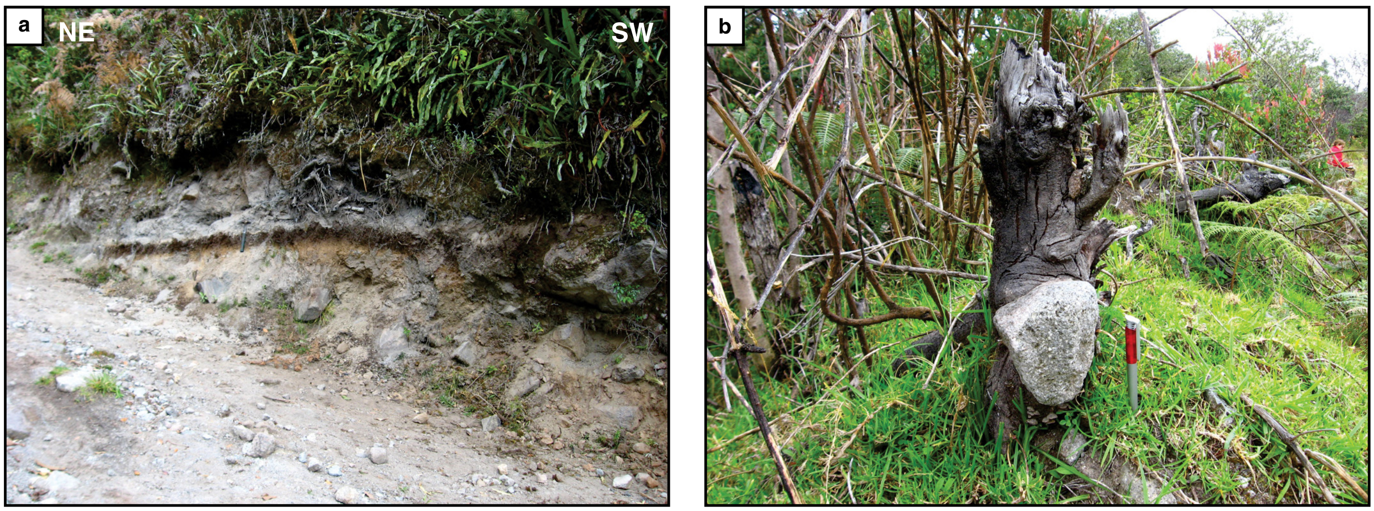


Figure 20. Material emitted by the Doña Juana Volcano during the 1897–1899 eruptive activity in the Valmaría sector, 5.5 km from the volcano. **(a)** Block and ash flow deposit generated by this eruptive activity and separated by a paleosol from another deposit of the same type. **(b)** Fifteen centimeter ballistic projectile embedded in a tree. Source: SGC database, Observatorio Vulcanológico y Sismológico de Popayán.

important pyroclastic deposit of pumice fall material previously attributed to the Doña Juana Volcano. The few available petrographic analyses show a mineralogical association similar to that of Doña Juana products, and geochemically, they are classified as dacites with 67.03 wt% SiO_2 (Pardo et al., 2016).

The Ánimas Volcano is considered active due to its well–preserved morphology, stratigraphic relationships with the Doña Juana Volcano deposits, and associated seismic activity (SGC, Observatorio Vulcanológico y Sismológico de Pasto, https://www.sgc.gov.co/volcanes).

4.2.3. Petacas Volcano

Located within the limits of Cauca and Nariño Departments, 66 km from Pasto, the Petacas Volcano has not been effectively studied, despite being mentioned in some works. In aerial photographs, the volcano seems to be eroded, and it is not possible to clearly distinguish the volcanic edifice (Monsalve & Terraza, 1996). Based on its morphology, Ceballos et al. (1994) classified it as a dormant volcano, while in the directory of volcanoes of the world (Simkin & Siebert, 1994), it appears as active with the number 1501–062, although the description could correspond to the Ánimas Volcano.

4.2.4. Sucubún Volcano

A gap of 55 km without active volcanism separates the Sucubún Volcano (Figure 22) from the set of volcanoes described above. This area is part of the Macizo Colombiano, where the Eastern and Central Cordilleras separate. The volcano is located between the Departments of Huila and Cauca 48 km SE of Po-

Figure 21. Aerial view of the summit of the Ánimas Volcano in 2007. A complex of domes and partial collapse deposits are observed. Source: SGC database, Observatorio Vulcanológico y Sismológico de Pasto.

payán, and it is part of a group of volcanoes aligned with an orientation of N20°W.

This volcano has not yet been studied; however, information about its products was collected during studies carried out on the Sotará Volcanic Complex, located 10 km to the NNW (Pulgarín et al., 2010). According to Orrego & Acevedo (1999), the Sucubún Volcano is located on the Guabas Fault with a WNW–ESE orientation.

The volcano is composed of the remnants of two concentric volcanic structures representing an external eroded caldera (Ceballos et al., 1994) and the current crater, which contains a dome 2 km in diameter (Pulgarín et al., 2010). This dome was previously referred to as Páramo of Socoboní (von Humboldt, 1800). In the 1993 1:25 000 topographic map (Plate 387–II–B) by the Instituto Geográfico Agustín Codazzi, referred to the volcano as Cerro Sucuzun. Products such as lava flow deposits, pyroclastic density flows, and domes are associated with this volcano.

Robertson et al. (2002) identified this volcano as Cerro San Alfredo and described another volcanic center on its southern flank that they identified as Ovejas, considering it a resurgent structure from which pyroclastic flows were generated.

Deposits that locally underlie very recent products from the Sotará Volcano seem to correspond to recent activity of the Sucubún Volcano or the Ovejas Volcano. The type of deposits indicates an origin from highly explosive events (Monsalve et al., 2011b). These deposits are grouped under the name Las Cabras eruptive unit and consist of lahars and a thick sequence of pumice flows, pyroclastic surges (Figure 23), and pumice falls with a wide distribution, reaching thicknesses of 6 m in Las Papas Valley (Pulgarín et al., 2010).

The activity of this volcano is unknown; however, von Humboldt (1800) provided the following description: "*Páramo of Socoboní, a high conical rock (dicunt) of black rocky texture, an ancient volcano that supposedly still rumbles*".

Figure 22. Panoramic image of the Sucubún Volcano dome located inside the eroded caldera–like structure. Taken from Pulgarín et al. (2010).

Figure 23. The sequence of pyroclastic surges in Las Cabras eruptive unit is attributed to the activity of the Sucubún Volcano, indicating the high explosivity of this volcano. Outcrop on Rio Blanco–Guachicono road, 9 km NNE from the volcano. Taken from Monsalve et al. (2011b).

4.2.5. Sotará Volcanic Complex

This complex is located on the border between the Departments of Cauca and Huila, 37 km SE of Popayán. The complex is composed of remnants of an old caldera (pre–Sotará), the Cerro Azafatudo and Cerro Negro volcanic structures, on the W flank, dating back to 500 000 y BP (Organización Latinoamericana de Energía & Geotérmica Italiana, 1982); resurgent volcanism has formed the Cerro Gordo Volcano on the edge and Sotará sensu stricto inside the caldera (Figure 24). The deposits associated with the volcanic complex consist of ignimbrites, lava flows, block and ash flows, surges, domes (including obsidian from Cerro Azafatudo), debris avalanches, pyroclastic falls, and lahars. The complex is associated with the San Jerónimo Fault.

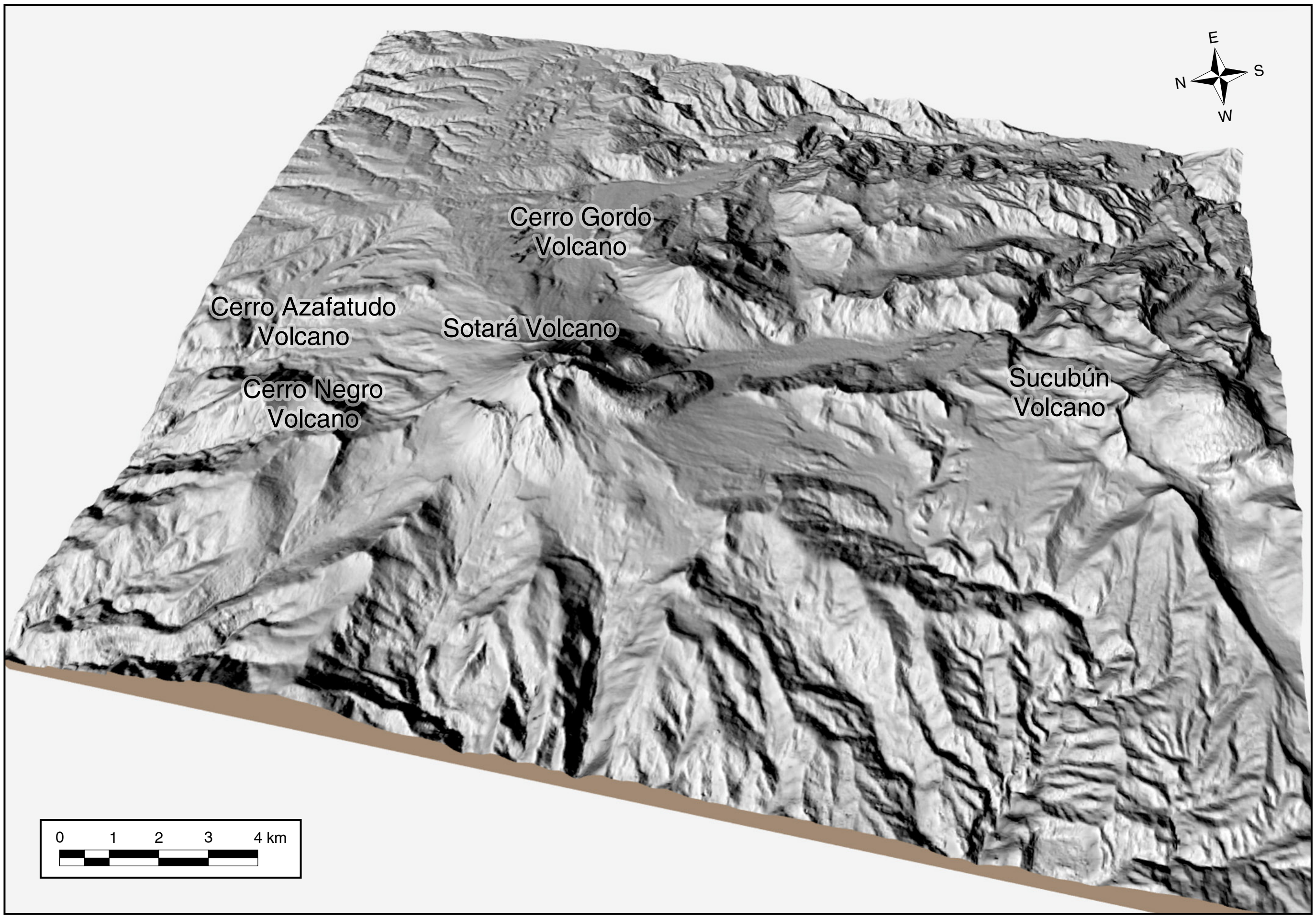


Figure 24. Perspective view of the existing structures in the proximal area of the Sotará Volcanic Complex (modified from Pulgarín et al., 2010).

According to Acevedo & Cepeda (1982), the Sotará Volcano is composed of three concentric calderas and endogenous domes. Pulgarín et al. (2010) described it as a structure in an amphitheater with an external crater 1.1 km in diameter and an internal crater 0.7 km in diameter. This crater includes a set of domes, one of which is a lava dome descending down the S flank to the base of the volcano (Figure 25). According to these authors, the volcano developed in three stages (Table 6) characterized by the extrusion and destruction of domes that generated pyroclastic density currents and debris avalanche deposits leading to hummocky surfaces.

Only one description of a possible eruption from the Sotará Volcano on 24 March 1893, was provided by The New York Times (1893a). This information has not been confirmed by historical archives, in the memory of the inhabitants of the region or via fieldwork. A later description of the phenomenon (The New York Times, 1893b) suggested that it was a massive landslide in the foothills of the volcano. An initial attempt to monitor the activity of the volcano was carried out for two months in 1966 (Minakami et al., 1969).

The Sotará Volcanic Complex is considered active due to the presence of thermal sources (Garzón et al., 1997), fumaroles located on the S and W flanks of the Cerro Gordo Volcano, and the associated seismicity. An increase in seismic activity started in 2010 (Alpala et al., 2017) with distant earthquakes that have migrated towards the volcanic edifice of Sotará, as well as gradual increases in deformation and fumarolic activity (SGC, https://www.sgc.gov.co/volcanes).

4.2.6. Coconucos Volcanic Chain

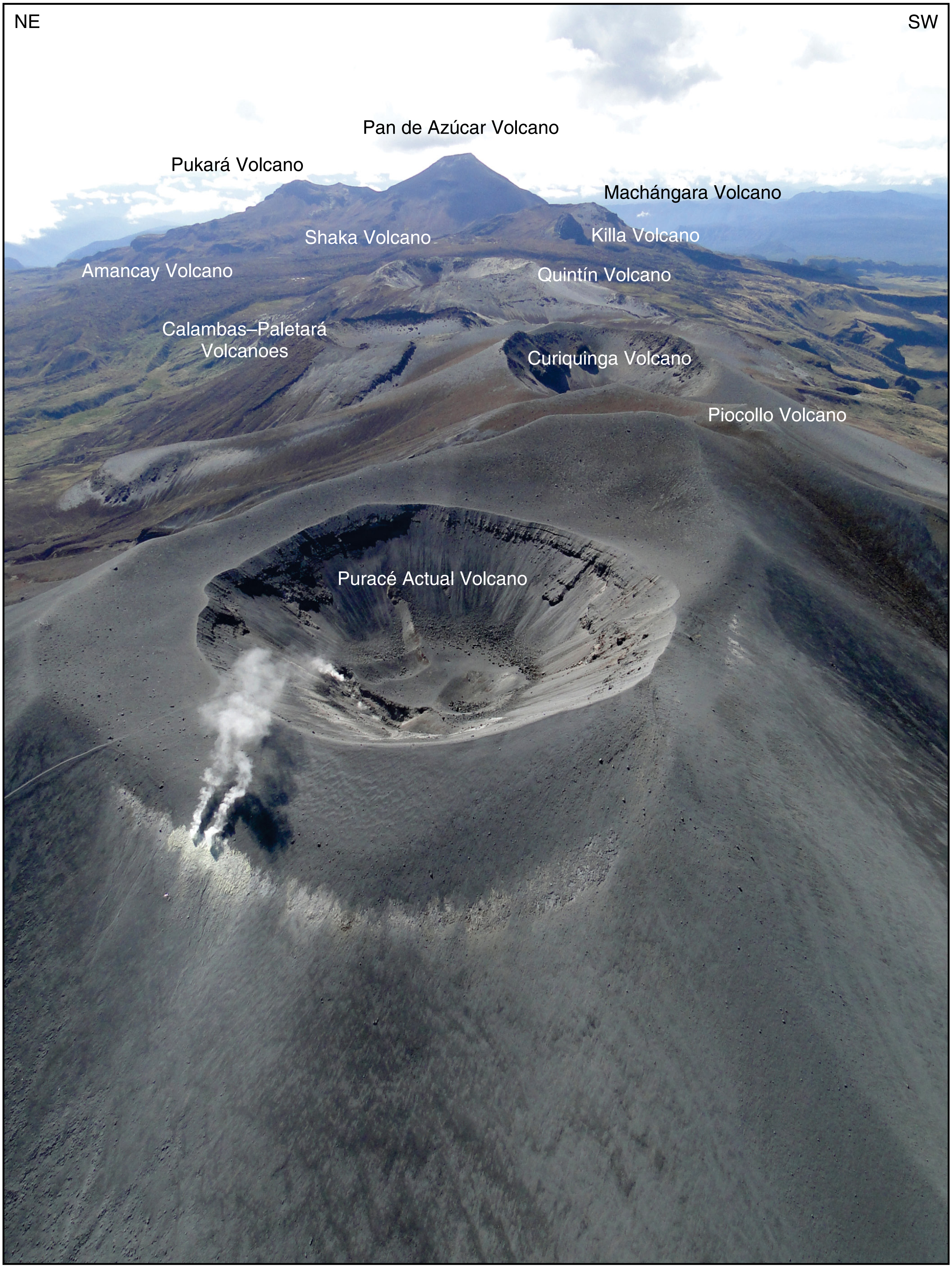
Located 28 km SE of Popayán, the chain is formed by a set of eruptive centers, with an orientation of N39°W along the Coconucos Fault. The Pan de Azúcar and Puracé Volcanoes lie at the SE and NW ends of the chain, respectively (Figure 26).

The Coconucos Volcanic Chain is located inside the Paletará Caldera (Figure 16), a structure 30 km in diameter. Associated with the Paletará Caldera, there is a thick sequence of rhyolitic ignimbrite deposits with ages between 7.1 ± 0.3 Ma and 2.1 ± 0.4 Ma, which reached the inter–Andean valleys on both sides of the Central Cordillera (Kroonenberg et

Figure 25. Sotará Volcano (2010) from the W: note the dome structures, with the most recent located inside the inner crater, and the lava dome to the right. Source: SGC database, Observatorio Vulcanológico y Sismológico de Popayán.

Table 6. Stages in the evolution of the Sotará Volcano (modified from Pulgarín et al., 2010).

	Stage	Acronym	Eruptive Unit	Associated deposits
Sotará Volcano	Stage 3	UE–DC	Domo Central y Domo Colada	Domes
		UE–PD	La Piedra	Pyroclastic density currents
		UE–LC	La Cima	Pyroclastic density currents
		UE–LA	Las Amarillas	Block and ash flows and surges
		UE–LD	Lavas de los Domos Somitales	Blocky lava flows
		UE–DS	Domos Somitales	5 domes
	Stage 2	DA–RN	Depósito de avalancha de escombros y Lahar Río Negro	Debris avalanche and lahar
		UE–LL	La Línea	Blocky lava flows
		UE–CO	La Corona	Blocky lava flows
	Stage 1	UE–LV	Las Vegas	Block and ash flows
		UE–LS	Llano de Sotará	Pyroclastic density currents, lahar
		UE–CU	La Cueva	Pumice and lithics flows
		UE–LP	La Paila	Block and ash flows
		UE–QC	Quilcacé	Block and ash flows
		UE–PU	Pujuyacu	Block and ash flows
		DA–PA	Depósito de avalancha de escombros Los Pajonales	Debris avalanche
		UE–ET	El Triángulo	Lava flows
		UE–DE	Domos Externos	Domes


NE
SW
Pan de Azúcar Volcano
Pukará Volcano
Machángara Volcano
Shaka Volcano
Killa Volcano
Amancay Volcano
Quintín Volcano
Calambas–Paletará Volcanoes
Curiquinga Volcano
Piocollo Volcano
Puracé Actual Volcano

←

Figure 26. Panoramic view of the Coconucos Volcanic Chain in 2011. The vents are aligned between the Puracé and Pan de Azúcar Volcanoes. In the foreground is the cone of the Puracé Actual Volcano, topped by the crater with fumarolic activity. The gray material corresponds to ash remnants emitted during the historical eruptions of the volcano. Source: SGC database, Observatorio Vulcanológico y Sismológico de Popayán.

al., 1981; Monsalve & Pulgarín, 1997; Torres, 2010; Torres et al., 1999; van der Wiel, 1991). Pulgarín et al. (1996) considered that Los Coconucos Volcanic Chain represents the resurgent volcanism of this caldera, while Acosta (1980), on the basis of its anomalous position relative to the axis of the cordillera and its concentrated activity in the extreme NW, raised the possibility that the origin of the chain is related to a hot spot.

The Coconucos Volcanic Chain is composed of superimposed volcanic edifices from different eruptive epochs, and the oldest edifices are remnants with evidence of glaciation, such as the Chagartón Caldera located at the NW end, which has an age of 0.59 Ma (Ramírez, 1982).

The products emitted by the Coconucos Volcanic Chain consist of hydrothermalized breccias, massive lava flows, blocky lavas, pyroclastic density currents (scoria flows, pumice flows, block and ash flows, and surges), pyroclastic falls (ash–lapilli falls and ballistic bombs and blocks), and lahars. Recent activity has built volcanic cones (some partially destroyed), plugs, pyroclastic rings, and lava plateaus (Flórez, 1983; Monsalve et al., 2012). These recent structures can be divided into two morphological groups: the volcanoes of the NW sector, which are known as Puracé, Piocollo, Curiquinga, Calambas–Paletará, and Quintín that feature cones with wide craters and associated pyroclastic deposits, and those of the SE sector, which include Shaka (with three eruptive centers), Machángara, Pan de Azúcar, Pukará, and the adventitious Amancay and Piki, featuring small craters that have produced lava flows up to 10 km in length.

The Coconucos Volcanic Chain is considered active based on its well–preserved morphology, Holocene products, and hot springs (i.e., Koller & Aucott, l986; Mojica & Cañon–Romero, 2000; Sturchio et al., 1993), as well as on the historical eruptions and fumarolic activity of the Puracé Actual Volcano, which has been studied in greater detail than the other volcanoes because it is the most active volcano in the chain (Oppenheim, 1950) and because a sulfur mine lies on its slopes (Megyesi, 1962).

The Puracé Actual Volcano is the most recent edifice of the Puracé Volcano; it has a truncated pyramid shape with a double crater rim (Figure 26). Its activity began 8000 y BP, and its products were grouped into eruptive units by Monsalve et al. (2012).

According to Arboleda (1990), Puracé means "mountain of fire" in the tradition of the inhabitants of Puracé, which indicates its activity in the pre–Hispanic epoch. The activity is confirmed by the presence of ceramics in the paleosols between volcanic deposits, which indicate the occupation of the middle and proximal parts of the volcano's edifice (Table 7) and the possible displacement of the populations due to the eruptions in this epoch (Patiño & Monsalve, 2015, 2019). The activity of this volcano has been recorded historically since the 16th century, and it has been better documented since the 19th century (Espinosa–Baquero, 1989, 2011, 2012; Ramírez, 1975).

With the available data on the activity at the time of the conquest and earlier, the volcanic deposits identified in the field are correlated with the so–called Cenizales eruptive unit (pre–Hispanic to conquest epoch) and the Histórica eruptive unit, which covers the activity from 1849 to 1977, the year in which the last eruptive phase occurred (Pulgarín et al., 1994). During this last period, the volcano had at least 35 eruptive phases; the more powerful events were the eruptive phases of 1849 and 1869, while the other events were considered minor phases that produced ash emissions and ballistic projectiles. The activity between 1849 and 1977 was almost continuous, and it was interpreted as the vulcanian type (Table 8).

4.2.7. Nevado del Huila Volcanic Complex

Located within the limits of the Departments of Cauca, Huila, and Tolima, 83 km NE of Popayán and 80 km NNE of Los Coconucos Volcanic Chain, in the volcanic gap between the central and northern volcanic segments, the Nevado del Huila Complex is the highest volcanic structure in Colombia (Figure 27). This complex has an elliptical morphology, and its top is covered by a glacier that at the beginning of 2007 had an area of 11 km^2 (Pulgarín et al., 2009; Worni, 2008) but has decreased since its reactivation in February of the same year.

The Nevado del Huila Volcanic Complex was built in three main stages (Table 9; i.e., Correa–Tamayo, 2009; Correa–Tamayo & Ancochea, 2015b; Correa–Tamayo & Pulgarín, 2002; Pulgarín et al., 2001). In addition, Correa–Tamayo (2009) recognized two substages: pre–Huila (1.6 Ma to the base of the sequence) and Huila, divided into Ancient Huila and Recent Huila (<10 000 years), this one formed by several peaks aligned N–S, without visible craters (Cepeda et al., 1986). The most recent activity was registered between the central and southern peaks since its reactivation in 2007 (Figure 27). Velandia (1997) located the Nevado del Huila Volcanic Complex inside a graben in the basement limited by NW–oriented faults.

The volcanic complex has predominantly emitted lava flows. Other volcanoclastic deposits include a volcanic debris avalanche formed between 20–46 ky (Pulgarín, 2000). In addition, some pyroclastic deposits of block and ash flows and pumice flows have been associated with the activity of Recent

Table 7. List of eruptive units and defined deposits for the Puracé Actual Volcano and data on occupation in the region according to Patiño & Monsalve (2015). Type of activity: (Ph) Phreatic; (PhM) phreatomagmatic; (V) vulcanian; (P) pelean; (E) effusive (taken from Monsalve, 2014a).

Eruptive unit	Age (years BP)	Predominant activity and deposits	Pre–Hispanic occupation
Histórica	Date: 1849–1977	V: Block and ash flows, ash and lapilli falls, scoria–pumice flows, surges.	
	140 ± 30		
Cenizales	Before 1849	PhM–V: Ash flows, ash falls, surges, phreatic flows, lahars.	Cristales
Colibri	?	PhM: Ash flows and hydrothermalized lithic flows (phreatic)	
	510 ± 30		Chiliglio
Granizo	610 ± 30	P–V(?): Dome explosion. Block and ash flows, surges, lahars.	Alto Anambio
Cristales	1160 ± 30	PhM: Pyroclastic falls, surges with archaeological remains.	Hispala, Cristales, Paletará, Paguimbio.
	1180 ± 30	Paleosol with lithic fragments	
6	?	V(?): Block and ash flow	
	1460 ± 30	Black paleosol	
		Lahar	Campamento, Poblazón
	1610 ± 30		
		Lahar	
7	1730 ± 30	PhM–V: Surges and block and ash flow	
	1780 ± 30		
Vinagre	2130–2050–2020 ± 30	PhM: Scoria flows, surges, pyroclastic falls (?).	Paletará, Patugó.
	2230 ± 30	Paleosol	
		Lahar	
	2420 ± 30	Paleosol	
		Lahar	Puracé
9	2500 ± 30	PhM: Gray surges	
10		Ph–PhM: Hydrothermalized lithic flows (phreatic)	
11	2810 ± 30	PhM: Surges	
	2840 ± 30	Paleosol with altered lithic fragments	
Agua Blanca	?	PhM–V: Block and ash flows and surges	
	3980 ± 30	Paleosol with lithic fragments	
	4680 ± 40		
Conjunto Lavas somitales	?	E: Lava flows	
	5650 ± 40		
Pirocl. De Anambio		PhM: Surges, pyroclastic falls	
	5710 ± 30		
14		V(?): Block and ash flows.	
15		PhM: Surges, ash falls.	
16		Ph–PhM: Hydrothermalized lithic flows (phreatic)	
17	?	PhM: Scoria–pumice flow	
	6000 ± 40	Paleosol	
	6320 ± 30	Surges with archaeological remains	Campamento
Conjunto lavas rojas	?	E: Lava flows	
18		Ph–PhM: Hydrothermalized lithic flows (phreatic), surges.	
	7800 ± 40		
Cocuy		PhM–V(?) Extrusion and destruction of dome, block and ash flows.	
20	8230 ± 40	PhM: Surges	
Depósitos hidrotermalizados (DH)	<10 000	Ph–PhM: Ash flow, hydrothermalized lithic flows (phreatic), hydrothermal breccia.	

Table 8. Summary of the historical activity of the Puracé Actual Volcano (taken from Monsalve, 2014a).

Phenomena	Nº. Events	Year	Day/month/hour	Comments
Eruption		1540–1560		
Explosions	2	1816	1 or 2 June nighttime, and 12 December.	Explosions and ash fall emissions
Seism	0	1827	16 November, 6:00 p. m.	Seism, no eruption.
Fumarolic activity	0	1827	18 November	Activity
Eruption	1	1830		Without support
Fumarolic activity	0	1831	20 April	Activity “Steam Currents” T 86 ° “one hundred chimneys”
Explosions	1	1835	23 January	Phreatic eruption
Explosions	1	1840		Explosion from central crater
Fumarolic activity	0	1847	27 October through 1852	Activity
		1848		Possible confusion of date
Eruption	2	1849	November (?), 4 December.	Eruption of mud–ash–column. Destruction of cone (half–orange shape), resulted in crater of 100 m. Ashes to the village of Tambo.
Eruption	1	1852		Ash
Eruption		1859		Set of eruptions
Eruption	3	1869	January nighttime (?). 4 October , 3 a. m. 6 October, 3:00 p.m.	Crater measured 550 m from east to west and looked like a bonfire; lava and ash in the river; projectiles to Popayán; then, a mass appeared inside the cone.
Fumarolic activity		1875		Fumarolic activity
Eruption	2	1878	31 August , 11 a. m. 11 September.	Ash fall
Explosions	1	1881		Explosion from central crater
Explosions	1	1885	25 May	
Explosions		1889		
Eruption	1	1899	4 November	Ash
Explosions	2	1906	29 September, 9:30 p. m. 21 November, 6:15 p. m.	
Explosions	1	1907	12 January, 6:30 p. m.	Ash, igneous material.
Explosions	1	1912	6 October, 9:00 p. m.	
Explosions	1	1914	5 August, 6:30 p. m.	
Explosions	2	1919	24 and 25 January, 6:00 p. m.	Ash (sand)
Explosions	1	1920	5 January, 8:00 p. m.	Ash
Fumarolic activity	0	1924		Activity
Eruption	3	1925	9 July, 12 October, and 5 November.	Explosion from central crater
Eruption	2	1926	21 June, 2:00 p. m. September.	Fire and ash
Explosions	2	1927	8? October, nighttime.	Bursts and eruptions
Eruption	1	1931	6 July	Eruptions – lava
Eruption	1	1932	January	Fire column
Fumarolic activity	1	1933	9 July, 12 October, and 5 November.	Gases and ash on the slopes of the hill
Explosions	1	1936	2 or 3 August, nighttime.	Shock wave
Explosions	1	1939	19 September	Explosion, shock wave, ash over Popayán.
Explosions	1	1941	15 August, 5:00 p. m.	Explosion, shock wave, abundant ash over Popayán at 8 p. m.
Fumarolic activity	1	1944	February early morning hours	Activity, seism.
Explosions	1	1946	29 – 30? March, 2:20 a. m.	Seism felt in Popayán–explosion
Explosions	2	1947	2 April, 5:54 p. m. 27 April, 7:00 a. m.	7 a. m. Ash and lapilli from 5 to 10 mm for 10 km and fine ash in Popayán during the day until 6:30 p. m.
Explosions	3	1949	26 May, 11 June, August.	Explosion; gas emission, steam, volcanic bombs.
Explosions	2	1950	10 January, morning hours; 26 July, 2:00 a. m.	Little ash; violent explosion.
Explosions	6	1955	Between the months of March and September	6 eruptions
Explosions	2	1956	April, palm sunday (1 to 8); 20 June 20.	Ash
Eruption	1	1958	1 February	Eruption
Explosions		1977	19 March	Ash emission

Table 9. Stages in the development of the Nevado del Huila Volcanic Complex related to glacial stages (Correa–Tamayo, 2009).

Eruptive stages of Nevado del Huila Volcanic Complex (masl)	Glacial stages of the Nevado del Huila (masl)	Age of the glacial stages correlated with glacial stages of the Nevado del Huila Natural Park (years BP)
Recent Huila (> 4300 ± 100)	Huila 8 (4300–4550)	<1800 DC
	Huila 7 (4000–4250)	1600–1800 DC
Older Huila (4300 ± 100 to 3600 ± 200)	Huila 6 (3700–3950)	10 000–11 000
	Huila 5 (3500–3650)	14 000–20 000
	Huila 4 (3200–3450)	25 000–28 000
	Huila 3 (3050–3100)	34 000–40 000
	Huila 2 (2850–3000)	>48 000
Pre–Huila (3600 ± 200 to 2600 ± 100)	Huila 1 (2650–2800)	>100 000 ?

Figure 27. Panoramic view of the Nevado del Huila Volcanic Complex taken in 2008 from the E. The dome between the southern and central peaks was extruded in 2008. Note the traces of mudflows generated in 2007–2008. Source: SGC database, Observatorio Vulcanológico y Sismológico de Popayán.

Huila stage (Correa–Tamayo, 2009). In November 2008 and October 2009, domes were extruded.

The Nevado del Huila Volcanic Complex is active. In addition to eruptions in recent years and the presence of thermal springs, its fumarolic activity in the central peak has been described since the sixteenth century (i.e., Cornette, 1852; Espinosa–Baquero, 2011; Laverde & Pulgarín, 2014; Stübel, 1906). The word *Huila*, which is of indigenous origin, means "orange", and in the Páez language (Nasa Yuwe), it means "luminous mountain" (Gobernación del Huila, 2017). Similarly, to refer to the snowy mountain, the terms ñandy or *yändy* are used (Flórez & Ochoa, 1990).

Data on the historical eruptive activity of the Nevado del Huila Volcanic Complex are scarce. Espinosa–Baquero (2011) and Laverde & Pulgarín (2014) registered and analyzed the activity since colonial times and found that the first reference was by Mendel (1566, in Espinosa–Baquero, 2011), who mentioned "another volcano on fire" located "in the province of Timaná". The other references are related to large earthquakes attributed to eruptions of the volcano or its fumarolic activity from 1606 to 1940.

A more direct mention of its activity is found in extracts from letters addressed to M. Deshayes by Father Cornette (1852), who described the Nevado del Huila as follows:

"*... To the E* [referring to Popayán city] *appears the majestic central chain and the Guila Volcano, releasing from time to time vortices of smoke ... During my stay in this city* [Popayán]*, on Wednesday, October 27, at approximately twelve–thirty of the day, a few leagues to the N of the city near Chilicas, a terrifying underground detonation was heard. A river stopped its course, then reappeared again, carrying clayey–sulfur materials. It was the Guila Volcano that had erupted ...*"

According to Perrey (1857), this eruption occurred in 1847 (effectively, 27 October of this year was wednesday). This activity was also mentioned by Dollfus & de Mont–Serrat (1868) without providing further details. Figure 28 is a watercolor painting by Manuel María Paz (Universidad Eafit, 2011) of the volcanic complex with possible signs of activity in 1853. In later years, the mention of Stübel stands out who on an excursion on 2 March 1869, towards the volcano, referred to its "persistent weak activity" (in Espinosa–Baquero, 2011).

In February 2007, signs of reactivation in the volcanic complex were detected, including increases and changes in the seismicity pattern (Santacoloma et al., 2009), which were the precursors of minor phreatic eruptive phases with ash emissions and lahar generation; later, magmatic phases emplaced domes (Ingeominas, 2007a, 2007b, 2007c; Monsalve et al., 2011c; Pulgarín et al., 2009; Worni, 2008). This activity continued until 2010, and since then, the seismic behavior has remained anomalous (SGC, https://www2.sgc.gov.co/sgc/volcanes/VolcanNevadoHuila).

4.3. Northern Volcanic Segment

The northern volcanic segment (Figure 29) is located 200 km north of the Nevado del Huila Volcano. The volcanoes of this segment were previously known as the Machín–Cerro Bravo Volcanic Complex. It is located in the central part of the Central Cordillera between boundaries B (Cartago) and A (Cañas Gordas) of Hall & Wood (1985) (Figure 5) and partially in the Cauca Segment of Pennington (1981). Bohórquez et al. (2005) located the volcanoes of the segment mostly on the axis of the mountain range, very near N–S–oriented lineaments. These authors considered that the volcanism in this segment is limited to the north by the NW–SE–oriented Pocito River lineament that crosses the mountain range near Romeral Volcano and to the south by the Chapetón–Pericos and Ibagué Faults near the Cerro Machín Volcano. According to Thouret (1988), most polygenetic volcanoes have an eruptive history of approximately 2 my, and developed along the Palestina Fault Zone at the intersection with NW–SE–oriented faults (Figure 3).

The volcanism of this segment is associated with a typical subduction process related to the 160 km–long trench between 4.0 and 5.5° N off the southern coast of Chocó. The Benioff zone is defined by intermediate seismicity (70 to 200 km) at distances of 200 and 350 km from the trench and at slab depths greater than 200 km, with a dip of 40° towards the ESE (Arcila & Dimaté, 2005). The volcanoes are located 300 km from the trench.

To the north of the limit of active volcanism and on the axis of the Central Cordillera, Ceballos et al. (1994), Flórez (2003), and Robertson et al. (2002) identified several partially eroded volcanic edifices by photogeology. Most of these edifices have not been studied, with the exception of the Romeral Volcano, where despite strong dissection, deposits of less than 10 000 years have been associated with its activity (Pinilla, 2005).

On the western flank of the Central Cordillera along the Villa María–Termales Fault (NW–SE), several volcanic domes and two small volcanoes called Tesorito and Gualí are aligned. Ceballos et al. (1994) considered these edifices to represent andesitic cones, the former in a subrecent inactive state and the latter in a dormant state. Murcia et al. (2017, 2019) identified this volcanic complex as the Villa María–Termales monogenetic volcanic field (Figure 29).

The San Diego Volcano, the northernmost volcano of the Andes, is located 70 km NE of the Cerro Bravo Volcano and off the axis of the mountain range. It had been considered an isolated volcano (Borrero et al., 2014, 2016; Toro, 1991), but recently, other eruptive centers were identified between these volcanoes (Monsalve, 2014b; Monsalve et al., 2019): El Escondido and Berlín, of late Pleistocene age. Additionally, Central Hidroeléctrica de Caldas S.A. & Ente Nazionale per L'energia Elettrica (Enel) (1981), suggested the existence of at least 10 circular structures in this area that could be associated with phreatic eruptions. Leal–Mejía (2011) reported subvolcanic

Figure 28. *Nevado del Huila seen from San Agustín, province of Neiva*. Watercolor painting by Manuel Maria Paz (1853, in Universidad Eafit, 2011). Note the shades over the glacier cap and the dark fumarole on the central peak.

bodies in the Río Dulce sector, some of which have been evaluated for mineral resources. Cerro Guadalupe, another structure in the vicinity of Manzanares (Caldas), was classified by Flórez (2003) as a volcano with slight dissection but in regional works had been mapped as intrusive (Barrero & Vesga, 1976).

In the southern part of the northern volcanic segment, monogenetic basaltic volcanoes are located near the town of Cajamarca and the city of Ibagué (i.e., Gómez et al., 2016; Monsalve & Gómez, 2015; Murcia et al., 2019; Núñez et al., 2001).

Petrographically, the volcanic products of the northern volcanic segment are classified as andesites and dacites, with mineralogical associations of Pg, Opx, Cpx, ± Ol, and Ox; Pg, Opx, Cpx, and Ox; and Pg, An ± Bi, and Ox. Geochemically, these products correspond to calc–alkaline andesites, dacites, and rhyolites (Figure 30a). The REE multielement diagram (Figure 30b) shows parallel patterns with marked enrichment in LREE and depletion in HREE, mainly for samples from the San Diego Maar. Additionally, the diagram reveals positive Tb anomalies for samples from the Santa Rosa and Nevado del Ruiz Volcanoes, positive Eu anomalies for samples from the San Diego Maar and El Escondido Volcano, and no Eu anomaly for samples of the Cerro Machín Volcano. The apparent Eu anomaly for the samples from the Nevado del Ruiz Volcano may be an error related to laboratory contamination (Martinez et al., 2014). In the discrimination diagram for adakitic and calc–alkaline rocks (Figure 31) of Defant & Drummond (1990), the rocks of the Cerro Machín, Cerro Bravo, El Escondido, and San Diego Maar Volcanoes plot in the adakite field, whereas the samples from the Nevado del Ruiz and Santa Rosa Volcanoes plot in the normal calc–alkaline field.

The adakitic affinity of the Cerro Machín Volcano was noted by Laeger et al. (2013), who noticed the influence of garnet on the petrogenesis of the dacites. Regnier (2015) explained this trend by enrichment of the source with slab sediments or crustal contamination. The Nevado del Ruiz Volcanic Complex shows adakitic affinity for the older phases, while the most recent products have a normal calc–alkaline tendency (Borrero et al., 2009; Martínez et al., 2014).

Since 2007, important changes have been detected in the activity of several volcanoes in this segment (Londoño, 2016). The most significant changes are as follows: (1) Reactivation of the Nevado del Ruiz Volcano in 2010, with an increase in the seismicity and subsequent eruptive activity with small ash emissions, as well as the emplacement of a small dome in the Arenas crater; (2) increased radon and CO_2 emissions detected at monitoring stations near Cerro Bravo and a subsequent sequence of deep LP seismicity (long–period earthquakes) in 2008; (3) increased radon and CO_2 emissions from the Cerro Machín Volcano and an increase in seismic activity; (4) regional deformation occurring between 2011 and 2013 located near the Santa Isabel Dome Complex at a depth of 14 km, which was detected by InSAR analysis (Lundgren et al., 2015); (5) increases in seismicity at several volcanoes of the segment (Figure 32), suggesting a state of unrest (Londoño, 2016); to this author, the changes are related to the presence of a deep magma chamber

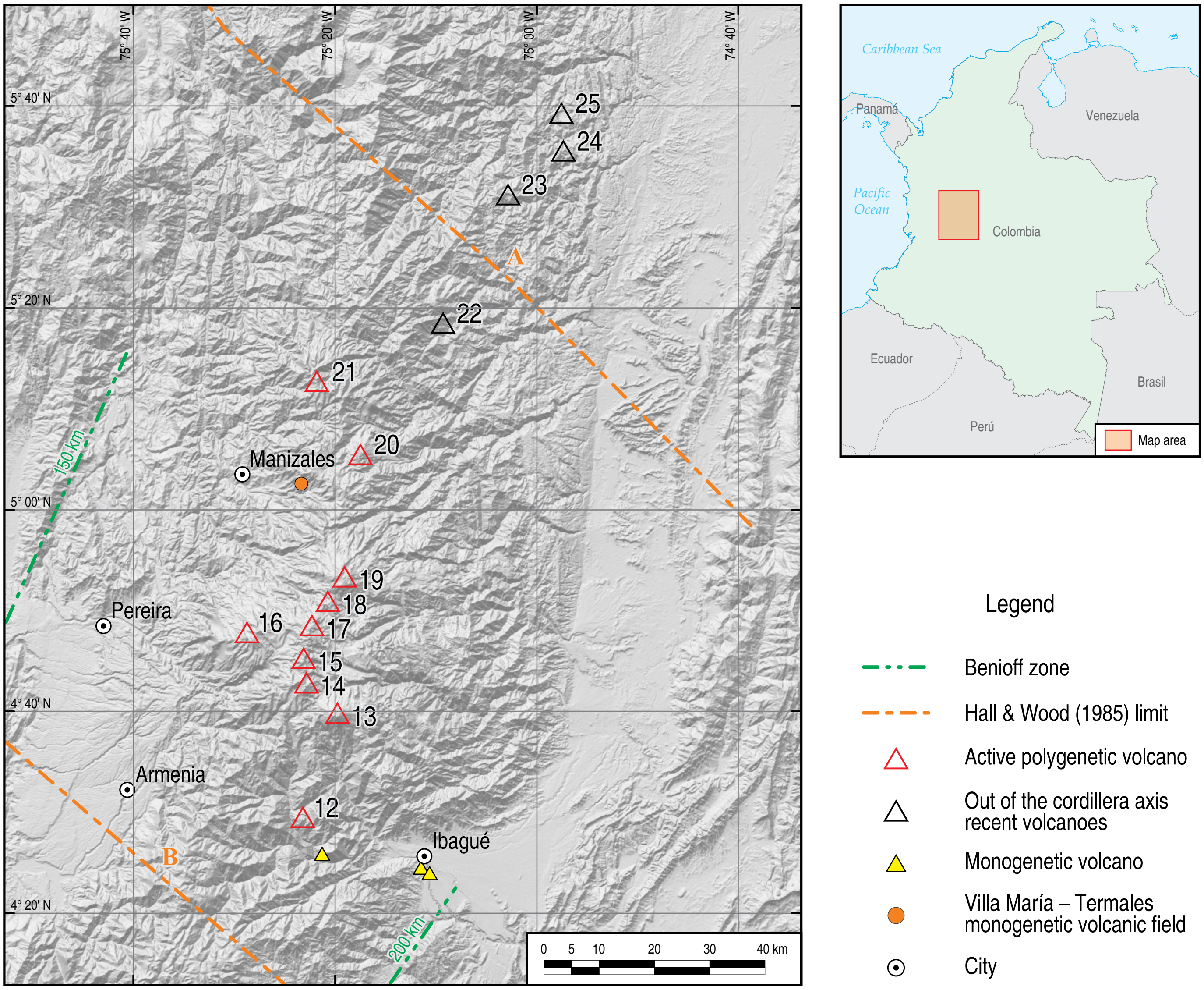


Figure 29. Locations of active volcanoes in the northern volcanic segment: (12) Cerro Machín Volcano, (13) Nevado del Tolima Volcano, (14) Nevado del Quindío Volcano, (15) Cerro España Volcanic Complex, (16) Paramillo de Santa Rosa Volcano, (17) Nevado de Santa Isabel Dome Complex, (18) Cisne–Morro Negro Volcanic Complex, (19) Nevado del Ruiz Volcanic Complex, (20) Cerro Bravo Volcano, (21) Romeral Volcano. Recent northernmost volcanoes off the cordillera axis: (22) Guadalupe Volcano, (23) El Escondido Volcano, (24) Berlín Maar, (25) San Diego Maar.

located between 20 and 40 km beneath the volcanic segment (Londoño & Dionicio, 2011).

4.3.1. Cerro Machín Volcano

Located 17 km W of Ibagué (Tolima), this volcano is a pyroclastic ring–dome complex of dacitic composition in the southern part of the northern volcanic segment, and it is 15 km off to the east of the cordillera. The volcanic edifice is located at the intersection of NE and NW–oriented faults. Osorio et al. (2008) suggested a close relationship between the Ibagué Fault and the Cerro Machín Volcano. The crater shows a diameter of 2.4 km, is open towards the SW and contains domes (Figure 33) with fumarolic activity. Aguilar & Piedrahíta (2017) classified the volcano as a tuff cone, whose crater is mainly composed of pyroclastic surges deposited during the last eruption at approximately 900 y BP.

Compared with the large polygenetic volcanoes of the cordilleran axis, the Cerro Machín Volcano has a short eruptive history of <50 000 years. The first eruptive record corresponds to the Boquerón Unit, dated to 47 100 ± 2400 y BP. Other dates have also been reported: 20 445 ± 210 y BP, 12 185 ± 200 y BP, 10 885 ± 95 y BP, and 8450 ± 95 y BP (Cepeda et al., 1996; Méndez, 2001). Existing works focus on the volcanic history of the volcano over the last 5000 years, during which 6 of the main eruptive stages have occurred (Table 10; Cortés, 2001; Méndez et al., 2002; Rueda, 2005).

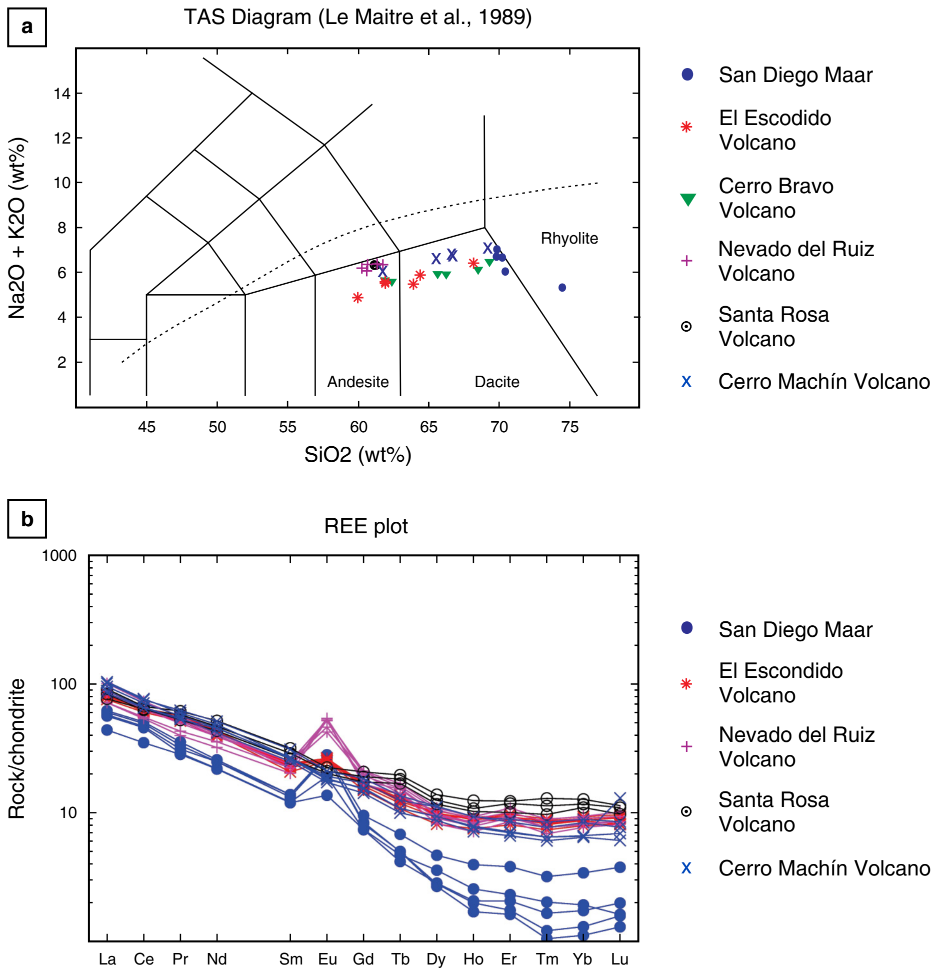


Figure 30. (a) IUGS TAS diagram for the classification of volcanic rocks (Le Maitre et al., 1989), with representative samples of the northern volcanic segment and volcanoes outside the axis of the cordillera. **(b)** REE diagram normalized to the chondrite data of Sun & McDonough (1989) for samples from the northern volcanic segment. Data from Lescinsky (1990a), Martínez et al. (2014), Monsalve (2014b), Narváez & Tobón (2007), Regnier (2015), and Vatin–Pérignon et al. (1990). No REE data are available for the Cerro Bravo Volcano. The diagrams were created with the PINGU tool (Cortés & Palma, 2018).

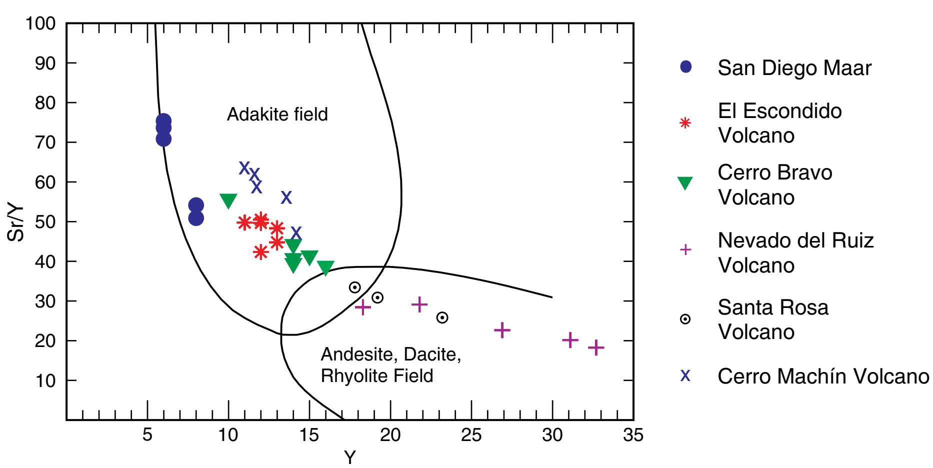


Figure 31. Adakite discrimination diagram (Defant & Drummond, 1990). The rocks of the Cerro Bravo, Cerro Machín, and San Diego Volcanoes plot in the adakite field. The samples from the Nevado del Ruiz and Santa Rosa Volcanoes range from normal to transitional calc–alkaline rocks. The data are shown in Figure 30.

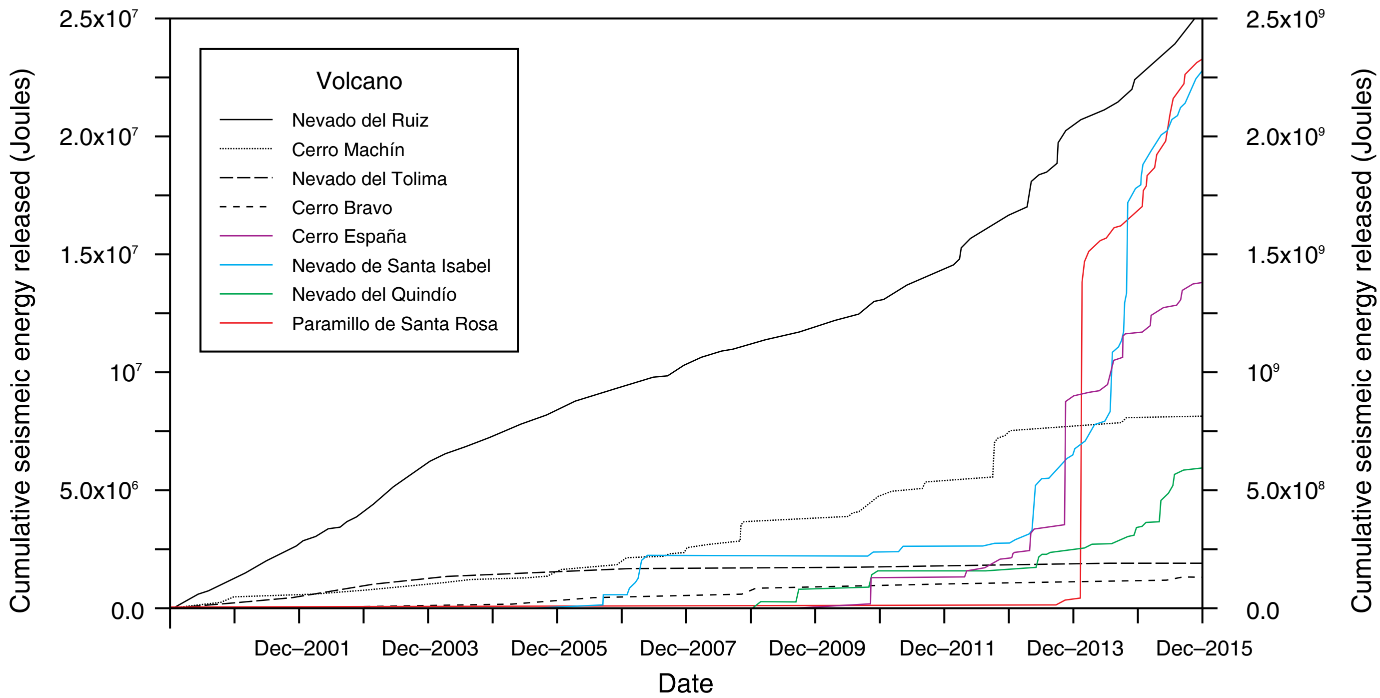


Figure 32. Cumulative seismic energy release for the earthquakes of the northern volcanic segment volcanoes between 2001 and 2015. Note the increase in the cumulative seismic energy release for each volcano. Right vertical axis corresponds to Nevado del Ruiz, Cerro Machín, Cerro Bravo, and Tolima Volcanoes. Left vertical axis corresponds to Cerro España, Nevado de Santa Isabel, Nevado del Quindio, and Paramillo de Santa Rosa Volcanoes (modified from Londoño, 2016).

The Cerro Machín Volcano generated plinian columns with heights up to 32 km, which originated pyroclastic falls that left deposits up to 10 cm thick at distances of approximately 50 km and pyroclastic density currents (pyroclastic flows and surges) and lahars that flowed several kilometers with volumes up to 22 km^3 (Cortés et al., 2001; Murcia et al., 2008, 2010; Rueda, 2005). These eruptions affected pre–Hispanic populations around the volcano (Cano et al., 2015).

The Cerro Machín Volcano is considered active based on its recent eruptive history, narratives of indigenous legends from the region (Bedoya, 1991), thermal springs, and fumarolic fields in the dome. Since 2007, the volcano has shown a gradual increase in its seismic activity (Figure 34), a change in deformation, an increase in the temperature of thermal sources and fumaroles, and the presence of new gas emission points in the dome (Inguaggiato et al., 2017; Londoño, 2016; SGC, Observatorio Vulcanológico y Sismológico de Manizales (SGC, https://www.sgc.gov.co/volcanes).

4.3.2. Nevado del Tolima Volcano

Located 28 km from Ibagué and 20 km N of the Cerro Machín Volcano, the Nevado del Tolima Volcano is off towards the SE from the axis of the Central Cordillera and from the main trend of the Palestina Fault. *Tolima* is an indigenous word meaning "supreme snow" (Velandia & Núñez, 1998). It is a cone–shaped volcano (Figure 35) with two craters located to the SE of the summit and is developed on successive caldera structures (Cepeda & Murcia, 1988). Deposits of basaltic lavas dated to 1.4 Ma by the whole–rock K–Ar method form the basement of these edifices (Thouret et al., 1995). Table 11 shows the eruptive history of the volcano.

The most recent eruptive period, dating from 16 000 years ago, corresponds to the development of the current edifice characterized by successive extrusion and destruction of domes during at least six eruptive stages, which generated lava flows, lava domes, deposits of block and ash flows, scoria flows, and ignimbrites. Similarly, debris flows were generated due to interactions with the glacial cap on the volcano. A Plinian phase occurred 3600 years ago, and small eruptions, possibly phreatic, occurred in historical times (Thouret et al., 1985, 1995).

The Nevado del Tolima Volcano is considered active due to the presence of fumaroles, thermal springs, associated seismic activity (Gil–Cruz, 1998), Holocene eruptions, and the reports of historical fumarolic activity and explosive eruptions that Hantke & Parodi (1966) indicated occurred in November 1822, March 1825, June 1826, May 1926, and March 1943. Thouret et al. (1985) attributed several layers of ash fall in the region not only to the Holocene activity of this volcano but also to activity in historical times (1932, 1943). However, Cepeda & Murcia (1988) did not find evidence of this historical activity.

4.3.3. Nevado del Quindío Volcano

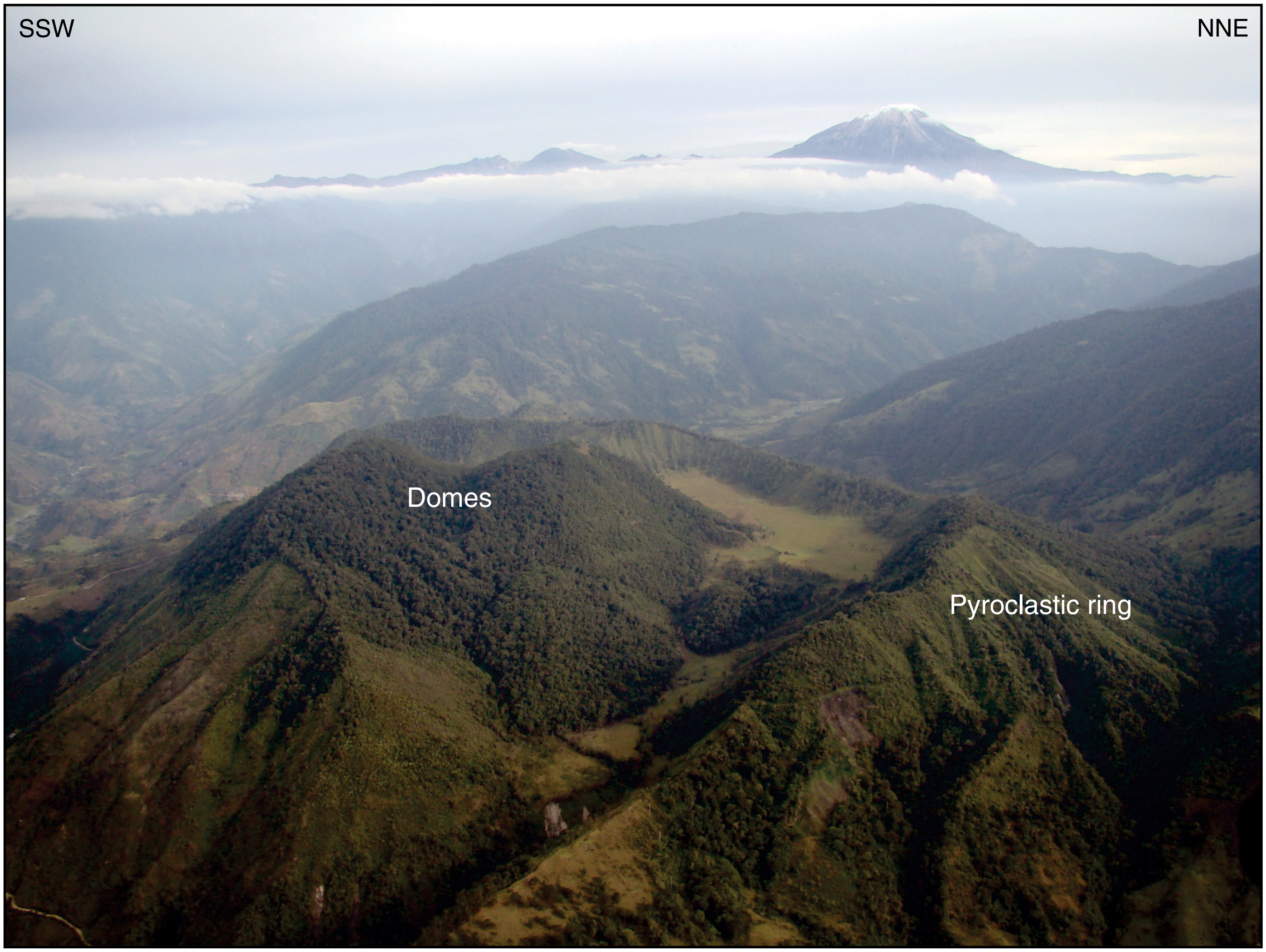


Figure 33. Panoramic view of the Cerro Machín Volcano in 2010 from the SW. In the foreground is the edifice with the pyroclastic ring that forms the crater, which is filled with domes. In the background is the Nevado del Tolima Volcano. Source: SGC database, Observatorio Vulcanológico y Sismológico de Manizales (OVSM), https://www2.sgc.gov.co/sgc/volcanes/VolcanCerroMachin/Paginas/Galeria-de-imagenes.aspx

Table 10. Main eruptive events at the Cerro Machín Volcano over the last 5000 years.

Unit (Méndez, 2001)	Unit (Rueda, 2005)	Age (years BP)	Deposits
Anillo	Anillo	900	Pyroclastic flows and surges, domes.
San Juan	P+2	1200	Pumice flows and pyroclastic falls, surges, lahars.
El Guaico	Guaico	2600	Block and ash flows, pumice flows, lahars.
Toche	P+1	3600	Pumice flows and falls, surges, explosion breccia, lahars.
Anaime–El Tigre	P0	4600	Pyroclastic flows and surges, pumice pyroclastic falls, ash falls, lahars.
Espartillal	Espartillal	5000	Pumice pyroclastic flows and surges, pumice pyroclastic falls.

Located on the axis of the Central Cordillera, 38 km from the city of Armenia (Quindío), this volcano has an eroded amphitheater shape (Figure 35), possibly due to collapses of the volcanic edifice and glacial activity. It was cataloged by Ceballos et al. (1994) as subrecent inactive and by Flórez (2003) as an eroded stratovolcano. This volcano features an eroded morphology with an amphitheater shape towards the N, NE, and SW sectors. This volcano has not been studied; howev-

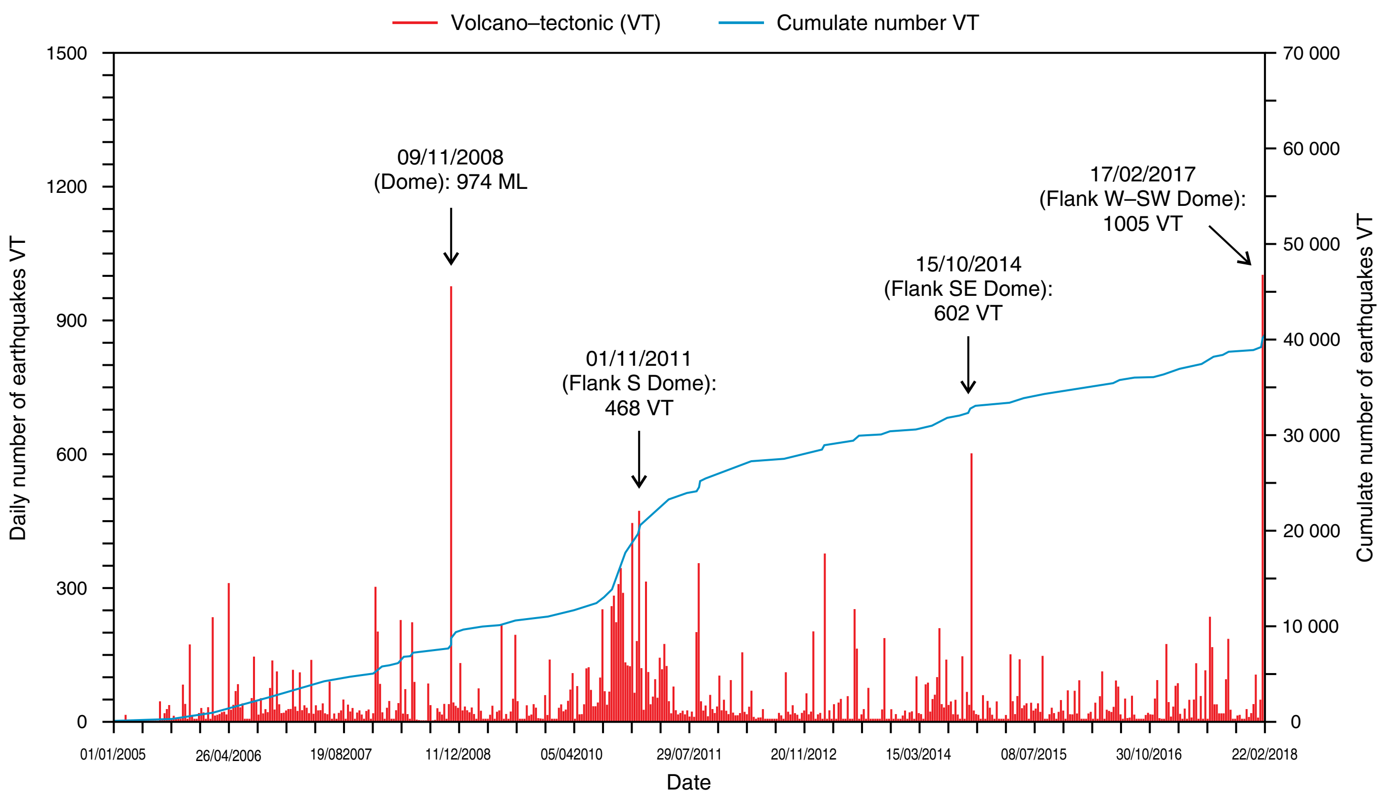


Figure 34. Daily number of volcanic–tectonic earthquakes (VT) in the Cerro Machín Volcano since 2005, showing the gradual increase in seismicity (source: SGC, OVSM.

er, the monitoring network of the Observatorio Vulcanológico y Sismológico de Manizales of the SGC has registered minor seismic volcanic activity in the vicinity of the edifice (SGC, https://www.sgc.gov.co/volcanes). This volcano has exhibited increased seismic activity since 2010 (Figure 32; Londoño, 2016); therefore, it has been classified as active.

4.3.4. Cerro España Volcanic Complex

Located 35 km W of Pereira (Risaralda) between the Nevado del Quindío Volcano and the Santa Isabel Dome Complex, the Cerro España Complex was described for the first time by Central Hidroeléctrica de Caldas S.A. (1983) as consisting of a caldera 2.5 km in diameter that contains domes that make up the Cerro España sensu strictu and several volcanic centers located on the W rim of the caldera, identified as Cerro Arenero, Cerros de Alsacia, and other volcanoes farther north, located outside the edge of the caldera. In general, Ingeominas (1992) and Errázuriz et al. (2017) refer to the set of these small volcanoes as Cerros de Alsacia. Recently, the SGC Observatorio Vulcanológico y Sismológico de Manizales (SGC, https://www.sgc.gov.co/volcanes) assigned names to each of these volcanoes, as shown in Figure 36.

The products emitted by these volcanoes are mainly lavas, such as the one emitted by the Otún Volcano that reaches a length of 12 km, enclosing a glacial valley and forming Otún Lake. An age of 5400 y BP is assigned to this lava by paleosol dating over the moraines cut by the lava and by the presence at the top of this lava of the layer of lapilli from Tolima Volcano dated to 3600 y BP (Ingeominas, 1992). Another lava flow originating from Cerro Arenero Volcano, identified by Thouret & van der Hammen (1981) as La Leona blocky lava flow deposit also encloses Holocene glacial valleys, indicating the recent activity of the volcanoes in this complex.

The lavas emitted by this group of volcanoes are two–pyroxene andesites with olivine and geochemically correspond to basaltic andesites with high MgO (Central Hidroeléctrica de Caldas S.A., 1983). Errázuriz et al. (2017) highlighted the compositional difference of these volcanoes with respect to the other volcanoes of the northern volcanic segment, as well as the difficulty of explaining their origins using the current models proposed for this segment. They therefore suggested a possible control based on variations in subduction parameters and their influence on the melting regime.

The Cerro España Volcanic Complex is considered active based on the Holocene age and on the associated seismicity and fumarolic activity south of the Otún Lake.

4.3.5. Santa Isabel Dome Complex

Located on the border of the Departments of Caldas and Tolima, 32 km SE of Manizales, this complex forms what is geo-

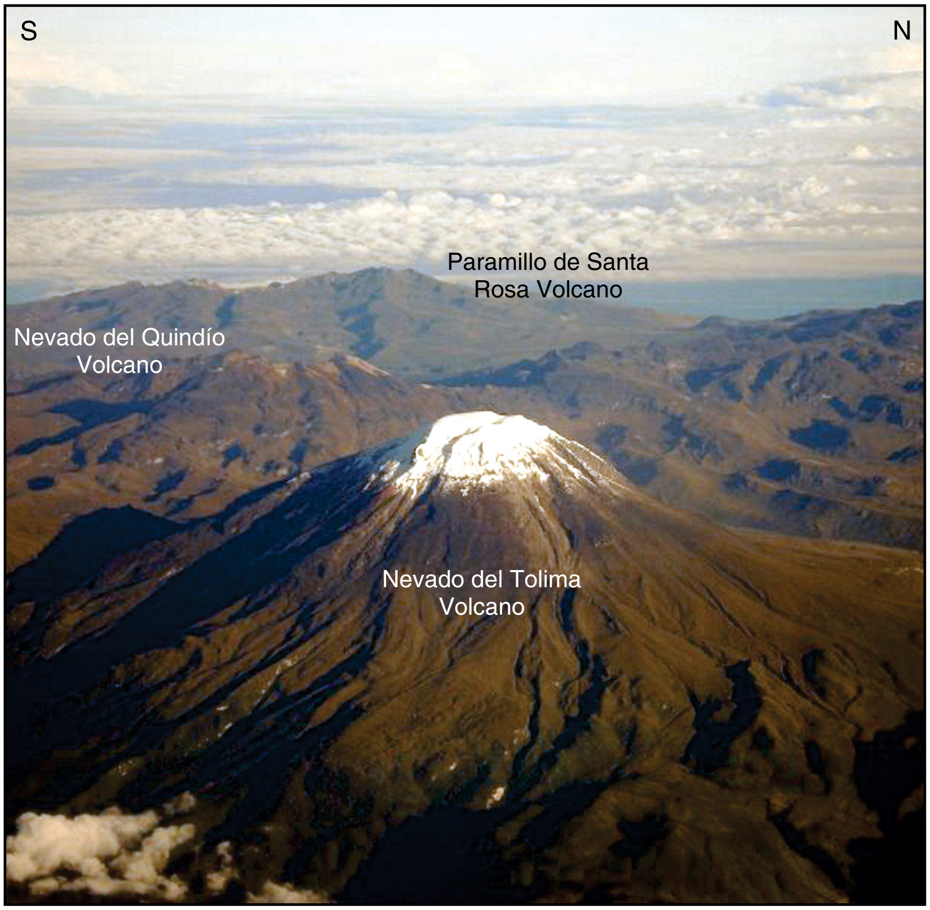


Figure 35. Panoramic view of the Nevado del Tolima Volcano in 2012 from the SW; the Nevado del Quindío Volcano is shown in the middle distance, and the Paramillo de Santa Rosa Volcano is shown in the background. Note the conical shape of the volcano. Source: SGC database, Observatorio Vulcanológico y Sismológico de Manizales.

graphically known as Nevado Santa Isabel (Figure 37). Central Hidroeléctrica de Caldas S.A. (1983) described it as a stratovolcano with a large edifice elongated along the volcanic axis (NNE–SSW) and covered by a glacier that masks its morphology and prevents the recognition of craters. In turn, Ingeominas & Corporación Autónoma Regional de Risaralda (Carder, 1993) described it as a set of domes and dome couleés located at the intersection of the Palestina (NE–SW) and Salento (NW–SE) Fault Systems and named it the Santa Isabel Dome Complex, including the northernmost volcanoes of the Cerro España Volcanic Complex because of their similarity.

Glacial retreat on the Santa Isabel Dome Complex has exposed at least 4 peaks that correspond to small volcanic edifices and domes developed on ancient volcanic structures, with associated lavas that have been dated by the K–Ar method to 0.76 and 0.68 Ma (Thouret et al., 1985).

The dominant products in the complex are blocky lava flow deposits, domes, and dome coulées, while the pyroclastic material is very scarce and corresponds to scoria flows, pumice flows, and block and ash deposits as well as pyroclastic surges and lahars. Some lavas have been dated to 5800 y BP (Ingeominas, 1992) in the eastern part, and a lava flow associated with the southern edifice extending 8 km to the E was dated between 6000 and 7400 y BP (Thouret & van der Hammen, 1981). According to Errázuriz et al. (2017), the lavas originating from this volcano correspond to more evolved andesites than those originating from the Cerros de Alsacia Volcanoes.

The Santa Isabel Dome Complex is considered active because of its Holocene products and associated seismicity.

4.3.6. Paramillo de Santa Rosa Volcano

Located 28 km from Pereira and 10 km W of the axis of the Central Cordillera (Figure 1), this volcano is described as a large stratovolcano (Figure 38) with a structure that has partially collapsed. In addition, the upper part seems dissected by dikes and exhibits strong hydrothermal alterations (SGC, Ob-

Table 11. Eruptive history of the Nevado del Tolima Volcano (Thouret et al., 1995).

Epochs		Volcanic period and phases		Eruptive stage	Age of recognized events
Historical				Las Nieves	1918? 1943? 1826, 1828
Holocene					ca. 1700, 2100, 2500 y BP
	Upper	Present Tolima	Destructive and constructive phases	Encanto	ca. 3600–3700 y BP
					ca. 4700–4900 y BP
	Middle			Mesetas	ca. 6250 ± 50 y BP
					ca. 7200 ± 50 y BP
	Lower				ca. 9750–10000 y BP
				Canalones	ca. 10800–11500 y BP
		Young Tolima	Destructive and constructive phases	Romerales	ca. 12300–13000 y BP
				El Placer	ca. 14000–16200 y BP
Pleistocene	Late		Destructive phase	Combeima	>0.04 and >0.14 Ma
					0.14 ± 0.03 Ma
	Upper	Older Tolima	Constructive phase	El Rancho	0.2 ± 0.09 Ma
	Middle				0.37 ± 0.1 Ma
			Destructive phase	Boquerón	>0.4 ± 0.07 Ma
	Lower				<0.68 ± 0.15 Ma
		Ancestral Tolima	Constructive phase	Porfias–Honduras	1 ± 0.05 Ma
					1.3 ± 0.15 Ma
Lower Quaternary		Pre–Tolima	Constructive phase	Totare	>1.4 Ma

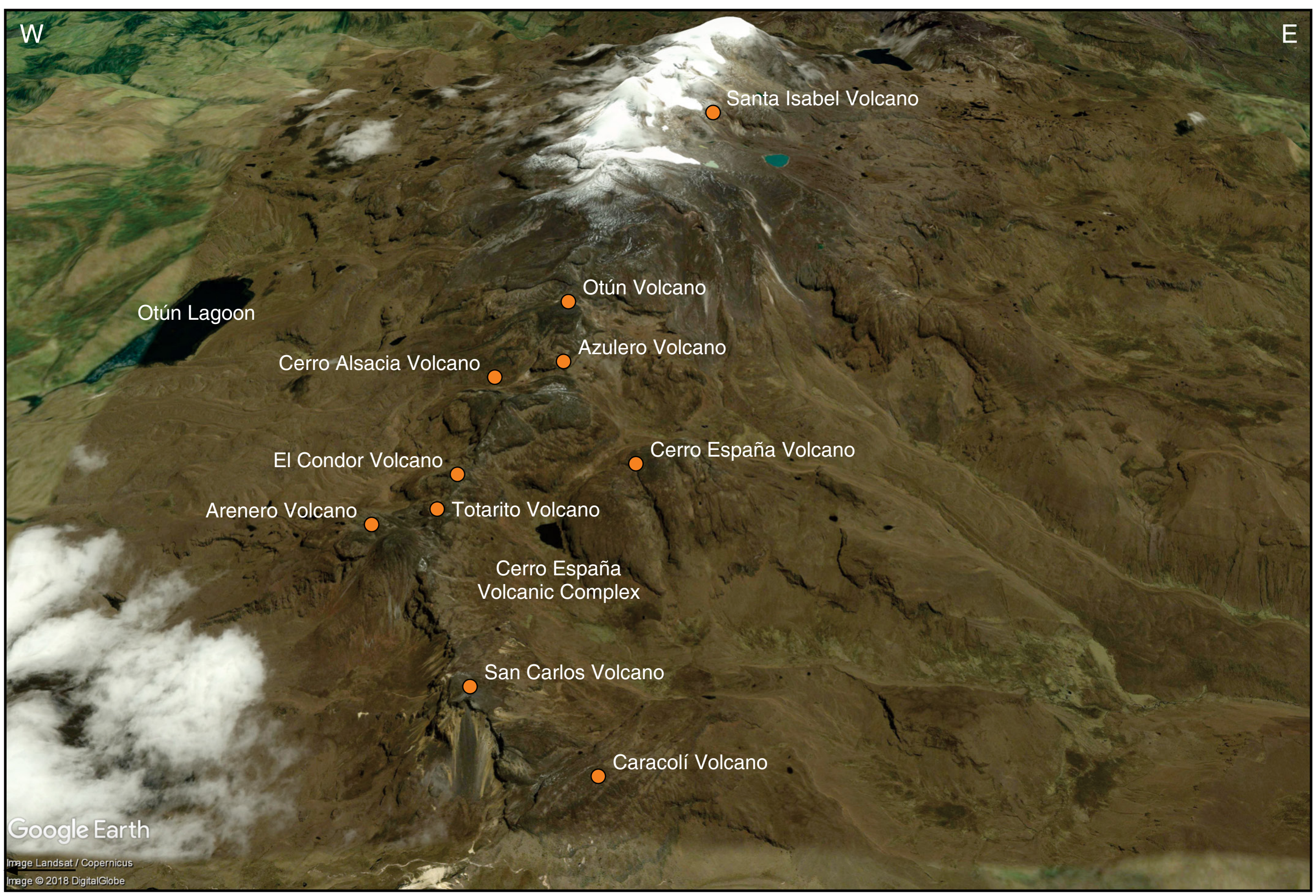


Figure 36. Google Earth image showing the Cerro España Volcanic Complex and the Cerros de Alsacia, located south of the Santa Isabel Volcano.

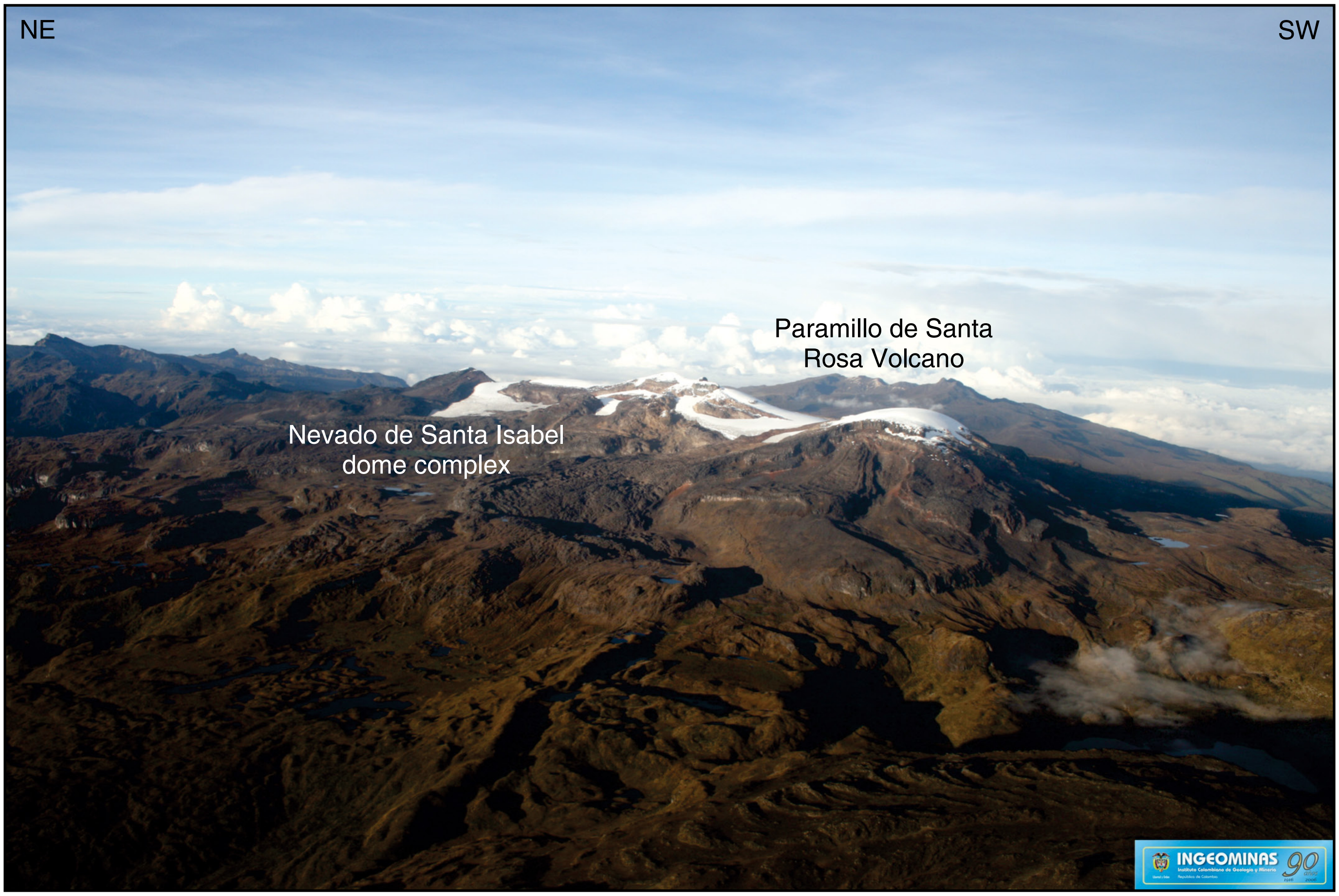


Figure 37. Panoramic view of the Santa Isabel Dome Complex in 2007 from the N. Note the Pliocene – Pleistocene lavas on which the dome complex is built; glacial retreat has revealed lava flow deposits from the northern edifice. The Paramillo de Santa Rosa Volcano is pictured in the background. Source: SGC database, OVSM, https://www2.sgc.gov.co/sgc/volcanes/VolcanNevadodeSantaIsabel/Paginas/generalidades-volcan-nevado-santa-isabel.aspx

servatorio Vulcanológico y Sismológico de Manizales, https://www.sgc.gov.co/volcanes). Studies on this structure have focused on geothermal exploration (i.e., Central Hidroeléctrica de Caldas S.A., 1983), and it is considered the oldest volcano in the segment, as evidenced by strong glacial erosion. Central Hidroeléctrica de Caldas S.A. (1983) suggested that its products correspond to evolved lava flows and ignimbrites.

Narváez & Tobón (2007) described lava flows from the so–called Tarapaca lava field with ages between 0.6 and 1 Ma with a possible origin from the Paramillo de Santa Rosa Volcano. González & Núñez (1991) argued that some deposits, mainly mudflows that make up the Glacis del Quíndío of Pliocene – Pleistocene age, originated in this volcano as well as other volcanoes of the northern volcanic segment. The first detailed volcanological studies were carried out recently, and the results are presented in this book (Pulgarín et al., 2020).

Despite its high degree of erosion, the volcano is considered active due to the occurrence of seismicity and important associated thermal springs (SGC, https://www.sgc.gov.co/volcanes).

4.3.7. Cisne–Morro Negro Volcanic Complex

Located 30 km SE of Manizales between the Santa Isabel and Nevado del Ruiz Volcanic Complexes (Figure 1), this volcanic complex was defined by Central Hidroeléctrica de Caldas S.A. (1983) as composed of at least 5 vents and 2 volcanic edifices with recent morphology: El Cisne and El Morro Negro 1 km to the E.

The complex was built on old stages of the Nevado del Ruiz–Nevado Santa Isabel Volcanic Complexes; its products are predominantly lava flows. It is considered active due to its associated seismicity.

4.3.8. Nevado del Ruiz Volcanic Complex

This complex is located 28 km SE of Manizales (Figure 1) and is composed of the following eruptive centers: the Arenas crater of the Nevado del Ruiz Volcano, La Olleta Volcano (Figure 39), the Piraña Volcano, and the Nereidas Volcano, a fissure lava and eight dome structures, most of which are located between the

Figure 38. Panoramic view of the Paramillo de Santa Rosa Volcano in 2011 from the W. Note the collapse of the flank towards this sector. Source: SGC database, OVSM, https://www2.sgc.gov.co/sgc/volcanes/VolcanParamilloSantaRosa/Paginas/generalidades-volcan-paramillo-santa-rosa.aspx

Nevado del Ruiz and the Cerro Bravo Volcanoes and are known as Alfombrales, Arenales, La Laguna, El Plato, Plazuelas, Recio, San Luis, and Santana (Martínez et al., 2014). The Nereidas Volcano was uncovered in 2007 by the glacial retreat of recent years (Duque, 2008).

The eruption of the Nevado del Ruiz Volcano in 1985 through the Arenas crater caused one of the greatest disasters of the 20th century worldwide. This event marked the starting point of systematic volcanic studies in Colombia, including monitoring and evaluation of volcanic hazards.

The first studies on the Nevado del Ruiz Volcano were carried out by Central Hidroeléctrica de Caldas S.A. (1983), Herd (1974), Jaramillo (1980), Ramírez (1982), and Thouret (1988). After its reactivation, this volcano became the most studied Colombian volcano (i.e., Lescinsky, 1990b and references therein). The most recent research (Martínez et al., 2014; Ceballos et al., 2016) was conducted to update the existing volcanic hazard map. The results of detailed volcanological studies in the Nevado del Ruiz are presented in this book (see Ceballos–Hernández et al., 2020)

Natives of the region used to call this volcano *Cumanday*, which means "beautiful bank", while others called it *Tama*, which means "Great Father" or "Big Father" (Espinosa–Baquero, 2012). The Nevado del Ruiz Volcanic Complex is considered active due to the presence of thermal springs; Holocene, historical, and current activity; high levels of seismicity; ash emissions; and slow dome extrusion at the bottom of the Arenas crater (SGC, https://www.sgc.gov.co/volcanes).

The Nevado del Ruiz is the only volcano from this complex with precise reports of historical activity. Espinosa–Baquero (2011, 2012) presented a complete compilation and analysis of this activity and produced transcripts of the events of 1595 and 1845. Similar to the eruption in 1985, these early events generated mudflows that affected the region where the city of Armero was later built.

4.3.9. Cerro Bravo Volcano

This volcano is considered the northernmost active volcano of the Andean Cordillera, and it is located in the Department of Tolima, 45 km NNW from Ibagué and 15 km E from Manizales (Figure 1). Herd (1974) was the first to identify Cerro Bravo as a volcano and to conduct tephrostratigraphic studies on its

Figure 39. Overview of the Nevado del Ruiz Volcanic Complex in 2011 from the W. La Olleta Volcano is located in the foreground to the right. Source: SGC database, Observatorio Vulcanológico y Sismológico de Manizales, https://www2.sgc.gov.co/sgc/volcanes/VolcanNevadoRuiz/Paginas/Galeria-de-imágenes.aspx

products. Its structure corresponds to a pyroclastic ring–dome complex (Figure 40). Previous studies classified it as a stratovolcano with migration of eruptive activity from S to N from a caldera known as Quebrada Seca and with an age greater than 15 000 years (Calvache et al., 1987; Central Hidroeléctrica de Caldas S.A., 1983; Lescinsky, 1990a; Monsalve, 1991; Ramírez, 1982; Thouret et al., 1985). This caldera is located within the volcano–tectonic depression of Letras that formed during the Pleistocene (Thouret et al., 1985).

According to Thouret et al. (1985), the activity at the Cerro Bravo Volcano started 1 my ago, with the formation of an ancient volcano in the early Pliocene and a modern volcano in the late Pleistocene and Holocene. Lescinsky (1990a) described the Cerro Bravo Volcano as a stratovolcano with an age of 50 000 y BP composed of three overlapping edifices, with remnants of domes in the two most recent ones. Studies underway to update the volcanic hazard map have reinterpreted its structure as consisting of dome remnants and pyroclastic rings generated by the successive extrusion and explosive destruction of domes (Figure 40).

In the geological record of the last 14 000 years, Herd (1974) recognized 17 units identified with the prefix CB, which Lescinsky (1990a) grouped into nine units (Figure 41), with the most recent (dated to less than 200 y BP) called CB1. These eruptive events represent explosive eruptions associated with the extrusion and destruction of domes, which generated block and ash flows, pumice flows, pyroclastic surges, and pyroclastic pumice falls as well as lahars. One of the block and ash flow deposits is welded, and it was interpreted by Alarcón (2017) as resulting from the destruction of a growing dome.

By studying the crystallization of one of the most recent domes, Pinzón & Echeverry (2017) identified the presence of magma chambers located at depths of 30 km and between 13.2 and 4.6 km under the volcano.

The Cerro Bravo Volcano is considered active due to evidence of Holocene activity, the presence of thermal springs (Gil–Cruz, 2001; Monsalve & Núñez, 1992) and low–energy volcanic–tectonic seismicity. In December 2008, some LP (long–period) earthquakes were recorded in the volcanic structure, and this seismicity was preceded by an increase in CO_2

Figure 40. Overview of the pyroclastic ring–dome complex of the Cerro Bravo Volcano. Dome remnants are numbered from oldest to youngest (1 to 9). The remnant of dome 3 is in the background, and number 7 is a pyroclastic ring structure (taken from Monsalve et al., 2017).

emissions and radon gas in the soil in April 2008 (Global Volcanism Program, 2013; Londoño, 2016).

The historical activity of the Cerro Bravo Volcano is represented by pumice fall deposits dated to <200 y BP by Lescinsky (1990a), and these deposits tend to be distributed W–SW (Figure 42). Boussingault contributed the only known historical reference to an eruption that could correspond to this event, which he identified during his stay in Anserma Viejo in 1830 (Boussingault, 1994):

> "*...There, I stayed in the house of an indigenous mayor, who gave me what I vainly searched for, that is, the date of the famous rain of ashes that came from the east and that also fell in Cartago and Chocó: 14 March 1805, between 1 and 3 in the afternoon, when a sky of great purity suddenly darkened. In Anserma, a very heavy rain was expected, but what fell was a black ash with a sulfurous smell, launched by a volcano from the Páramo del Ruiz that covered the whole region.*"

This same story is mentioned in Espinosa–Baquero (2012), although a direct reference to an eruptive event of the Nevado del Ruiz Volcano is presented. However, no ashfall deposits that can be related to an eruption of this volcano in 1805 have been identified.

4.3.9.1. Volcanism to the North and Northeast of the Cerro Bravo Volcano

On the axis of the Central Cordillera to the north of the Cerro Bravo Volcano, there are several volcanic centers classified as eroded or inactive (i.e., Ceballos et al., 1994). Among them, the Romeral Volcano, which is located 16 km to the N–NW of Cerro Bravo, is a large volcanic structure strongly dissected by glacial erosion. The crater is approximately 5 km in diameter and open to the E. It was named Romeral Volcano by Flórez (2003), who obtained two ages for lavas deposits of 3.6 ± 0.36 Ma and 2.7 ± 0.19 Ma. Additionally, pumice fall deposits exposed in the western sector of the volcano overlap a paleosol reported at 8460 ± 200 y BP by Pinilla (2005), who associated these deposits with the activity of this volcano. In addition to these authors, Barrantes (2011) and Facio–Lince (2012) carried out analyses to distinguish these pyroclasts from the pumice falls emitted by the Cerro Bravo Volcano.

The lavas and pyroclasts of the Romeral Volcano correspond to andesites with mineralogical associations of Pg, An, Cpx, and Ox and of Pg, An ± Bi, and Ox (Izquierdo, 2008). The latter association is similar to that found in pumices in the Holocene deposits described by Pinilla (2005).

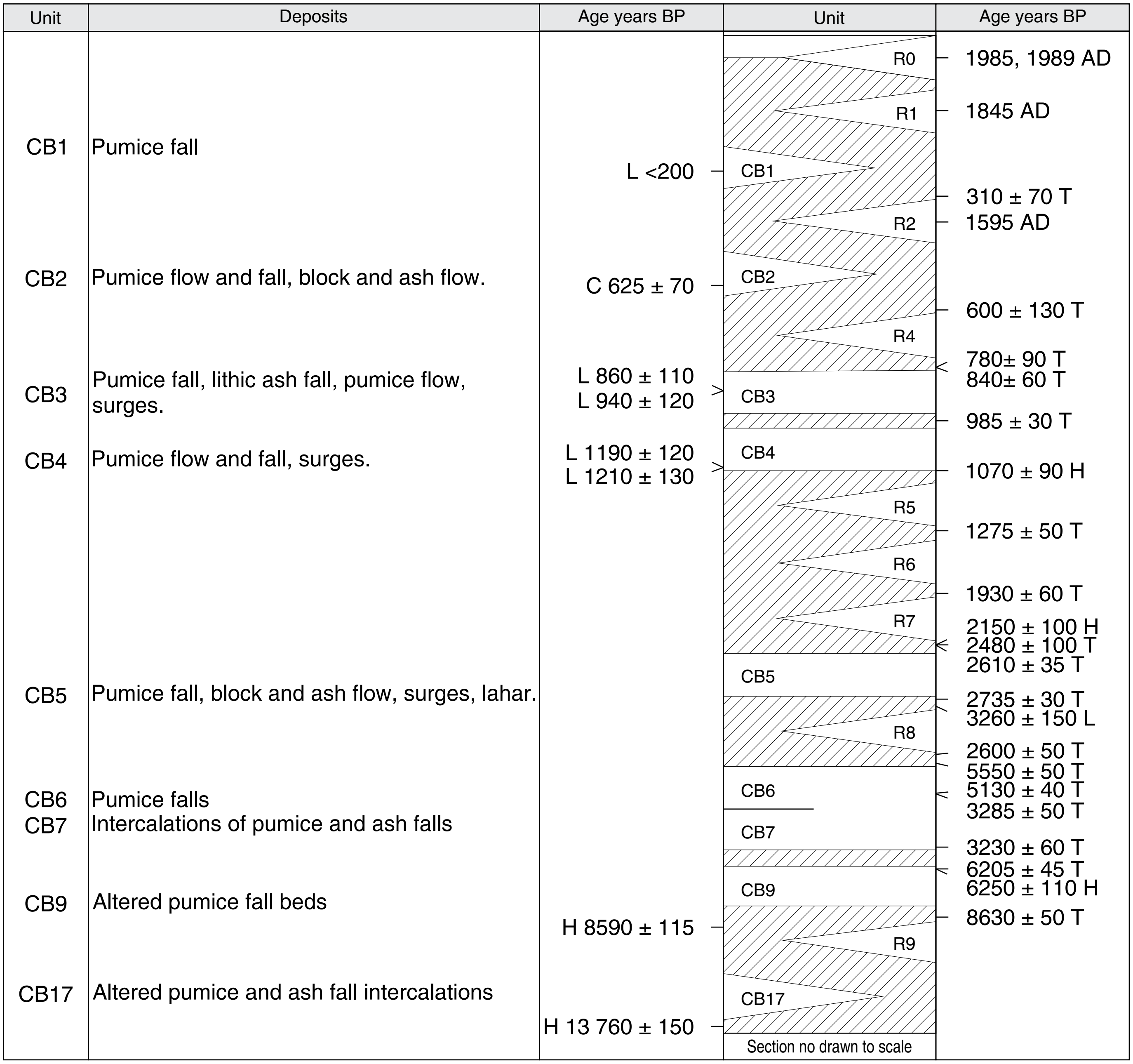


Figure 41. Deposits associated with the units defined by Lescinsky (1990a) and their relationship with the ages reported for the units of the Cerro Bravo (CB) and Nevado del Ruiz (R) Volcanoes according to various authors: (L) Lescinsky (1990a); (H) Herd (1974); (T) Thouret et al. (1985): (C) Central Hidroeléctrica de Caldas S.A. (1983). Taken from Lescinsky (1990a).

The ages obtained for pumice fall deposits associated with the Romeral Volcano would indicate that it is active. However, given the deeply eroded morphology of this volcano, further detailed studies are needed to verify this state. The seismological station located near the volcano reports no seismic activity of volcanic origin.

The northernmost Quaternary volcanism in the Andes is represented by outcrops of pyroclastic deposits, subvolcanic and volcanic structures located outside the axis of the Central Cordillera, NE of the Cerro Bravo Volcano (Barrero & Vesga, 1976; Borrero et al., 2014; Ceballos et al., 1994; Central Hidroeléctrica de Caldas S.A. & Ente Nazionale per L'energia Elettrica, 1981; Flórez, 1987, 2003; González, 1993; Jiménez, 2015; Leal–Mejía, 2011; Monsalve & Arcila, 2016; Monsalve et al., 2014, 2019; Toro, 1989, 1991). Some of these structures are aligned with the volcanoes of the cordillera and are oriented with the Palestina Fault Zone; they are inferred to represent recent volcanism in the region.

Central Hidroeléctrica de Caldas S.A. & Ente Nazionale per L'energia Elettrica (1981) referred to andesitic and dacitic

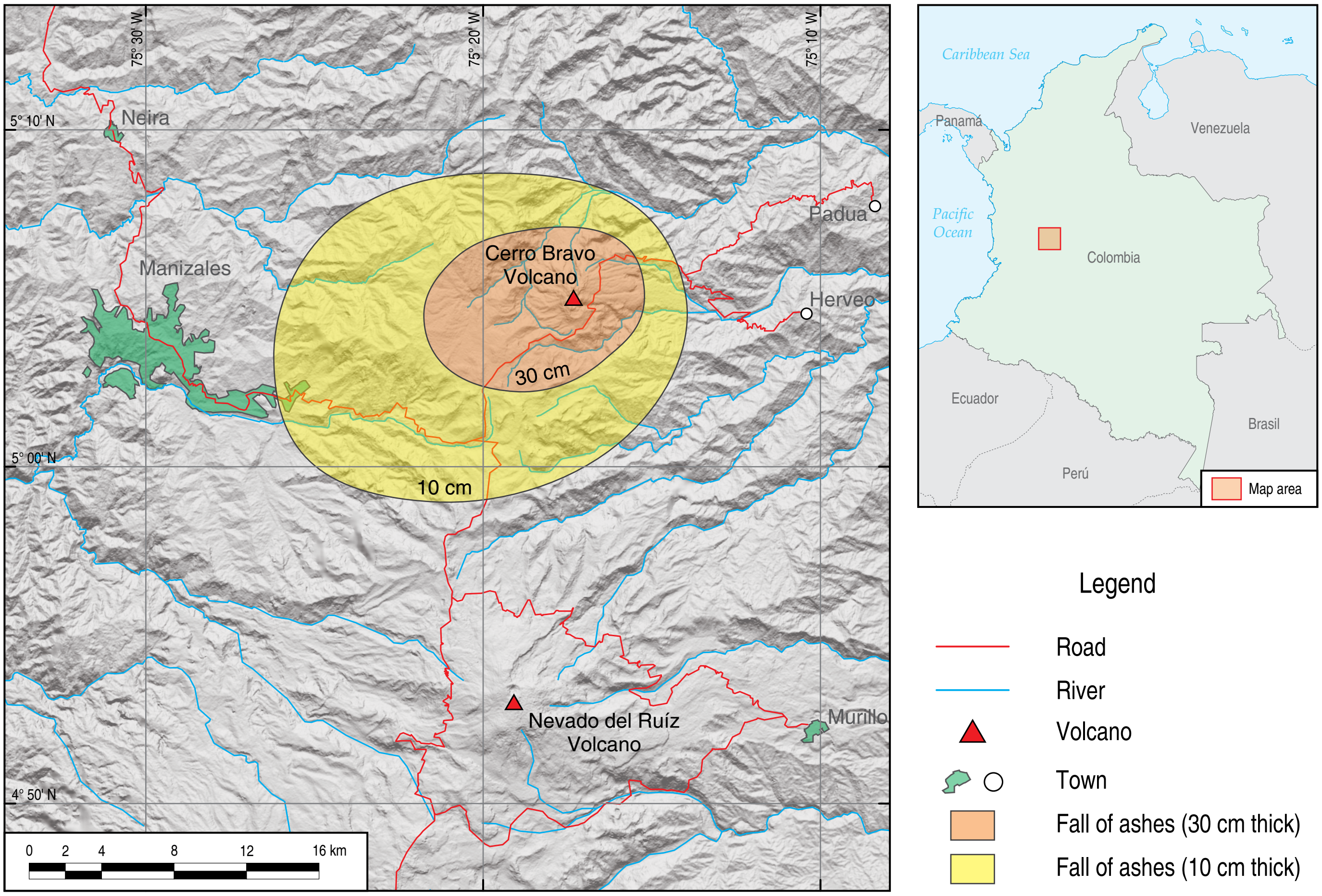


Figure 42. Isopachs of the eruptive event CB1 (<200 y BP) with W–SW dispersion. Modified from Lescinsky (1990a).

subvolcanic bodies associated with explosive processes that generated volcanic breccias and mentioned 10 circular forms attributed to possible phreatomagmatic processes without providing further details.

In the Río Dulce sector, Leal–Mejía (2011) reported ages between 2.4 and 0.4 Ma for hypabyssal intrusives and diatreme breccias (studied for ore exploration), indicating northeastward migration of magmatism. The author considered that these structures are genetically related to Pleistocene – recent coeval volcanic rocks that crop out in the northern volcanic segment along the axis of the cordillera.

Until a few years ago, the only volcano studied in this region was the San Diego Maar (Figures 29, 44) in the northernmost region of the Andean Cordillera. Additionally, Ceballos et al. (1994) identified the Guadalupe Volcano (Figure 29) on aerial photographs, and described it as a slightly dissected stratovolcano. Studies underway classify it as a dome complex with associated ignimbrite deposits, accretionary lapilli–rich pyroclastic surges, and block and ash flows.

Recently, in the Florence forest, 18 km SW and 8 km SE of the San Diego Maar, El Escondido Volcano and another circular structure called the Berlín Maar, respectively, were identified (i.e., Monsalve & Arcila 2016; Monsalve & Rueda 2015; Monsalve 2014b). These structures are evidence of recent volcanism, which Murcia et al. (2017, 2019) interpreted as a monogenetic volcanic field in a rear–arc position relative to the northern volcanic segment.

4.3.10. El Escondido Volcano

This volcano is a pyroclastic ring–dome complex type (Figure 43), corresponding to a "transitional" volcano in the terms of Smith & Németh (2017). The products associated with this volcano are block and ash flows, pyroclastic surges, pyroclastic pumice falls, ballistic projectiles, and domes (Monsalve et al., 2019). Dated to approximately 40 000 y BP, pyroclastic deposits of phreatoplinian origin cover an extensive region in the Departments of Caldas and Antioquia, and they are possibly associated with the initial activity of this volcano (Monsalve et al., 2019). Additionally, pyroclastic flow deposits have been dated to 36 030 ± 380 y BP and 33 550 ± 280 y BP. However, the age of the most recent products is unknown. Petrographical-

Figure 43. El Escondido Volcano. Note the dome within the interior of the crater. The edge of the crater is outlined by a dotted red line. The town of Florence is located on the eastern flank. SGC database, Observatorio Vulcanológico y Sismológico de Manizales, taken in 2016.

Figure 44. San Diego Maar Volcano crater in 2013, the northernmost Quaternary volcano of the Andean Cordillera. Inside the partially eroded El Morro tuff cone and plug. Source: SGC database, Observatorio Vulcanológico y Sismológico de Manizales, https://www2.sgc.gov.co/sgc/volcanes/VolcanSanDiego/Paginas/generalidades-volcan-san-diego.aspx

ly, the erupted material consists of amphibolic andesites. Geochemically, the material corresponds to calc–alkaline andesites and dacites with an adakitic tendency.

4.3.11. Berlín Maar

This is a circular structure 1 km in diameter, and the associated deposits underlie the phreatoplinian pumiceous layers from El Escondido Volcano. The deposits associated with this maar correspond to pyroclastic surges with accretionary lapilli and volcanic breccias generated by phreatomagmatic activity. These deposits form a ring around the crater and similarly crop out in the interior of the structure.

4.3.12. San Diego Maar Volcano

Morphologically, the San Diego volcanic structure (Figure 44) has maar and pyroclastic ring characteristics and is another example of transitional volcanism, evidenced by three evolutionary stages. The San Diego Maar has a pyroclastic ring around a 2.5 km–diameter crater occupied by a lake. The pre–eruptive basement is exposed in the walls of the crater, and a tuff cone called El Morro has developed within the crater. The initial activity phase generated breccia deposits and pyroclastic surges, dated to 40 000 y BP (Monsalve & Toro, 2016), that locally are interfingered with the phreatoplinian pumice deposits from El Escondido Volcano. A subsequent stage generated a sequence of pyroclastic surges, and a paleosol, which locally underlies these deposits and was dated by Borrero et al. (2016) to 16 000 y BP.

El Morro tuff cone is composed of a thick sequence of pyroclastic density current deposits, with layers enriched in accretionary lapilli and a rhyolitic plug (Toro, 1991), which has partially collapsed towards the NW.

Petrographically, the products associated with the activity of the San Diego Volcano correspond to dacites with a mineralogical association of Pg, Qz, Bi, and Ox. Geochemically, these rocks correspond to calc–alkaline dacites and rhyolites with adakitic affinity.

The recent volcanism (<50 000 y BP) to the NE of the Cerro Bravo Volcano is located in the transition zone defined by Monsalve–Jaramillo (1998) between 5 and 6° N along the subduction zone of the Nazca Plate. Pennington (1981) related the termination of active volcanism (described as Quaternary) to the fracturing of the plate, which represents the interaction of the Caribbean and Nazca Plates.

5. Final Considerations

The chapter summarized the state of knowledge about recent volcanism in Colombia and presented the distribution, characteristics, and activity associated with the volcanoes which particularities are the result of the tectonic configuration of the region. The NW corner of South America is a tectonically complex area featuring interactions among plates and microplates. In addition, the Panamá Basin has structures that affect the subducting Nazca Plate, leading to the development of the current tectonic setting and the characteristics of the volcanism that began in the Miocene and extend to the present.

Considering that systematic volcanological studies in Colombia began after the tragic eruption of the Nevado del Ruiz Volcano in 1985, it is understandable that studies on this natural phenomenon have focused on the most recent volcanism, especially those volcanoes considered active and potentially dangerous to communities in the surrounding areas. Five of these volcanoes have shown signs of reactivation or eruptions within the last 34 years.

Few studies have focused on the initial Miocene volcanism and that in the Pliocene – Pleistocene, on which the current volcanism developed; therefore, knowledge about the spatiotemporal evolution of this magmatism is lacking. The characterization of the Miocene volcanism is restricted to hypotheses based on the Combia Formation of tholeiitic affinity (i.e., Ramírez et al., 2006; Weber et al., 2020), which crops out to the north of the Andes in the Inter–Andean Cauca Valley in the Department of Antioquia, and the rhyolitic volcanism associated with large caldera structures south of the Central Cordillera, which produced extensive ignimbrite plains on both sides of the cordillera.

Pliocene – Pleistocene volcanic products crop out in the three cordilleras. In the southern Western Cordillera and in the Inter–Andean Patía Valley, these products form the subbasement for the current volcanism. In the Central Cordillera, these products are present almost continuously along the axis of the cordillera and extend slightly farther north from where the active volcanism ends. Similar to those of the Western Cordillera, the recent volcanoes of the Central Cordillera are built on these volcanic products; however, modern volcanism is not continuous, and certain sectors show only eroded edifices and deposits of Pliocene – Pleistocene age. In the Eastern Cordillera, in the Department of Boyacá, the Paipa Volcano and the Iza domes are located (Jaramillo et al., 2005; Martínez–Pérez, 1989; Monsalve et al., 2011d; Pardo et al., 2005) and represent Pleistocene volcanism whose origin is still debated.

The active volcanism in Colombia and Ecuador is part of the Northern Andean Volcanic Zone resulting from the subduction of the Nazca Plate under South America. Generally similar characteristics are attributed to all of this volcanism (i.e., Francis et al., 1977). However, Vanek et al. (1994) compared the compositions of recent volcanic rocks from Ecuador and southern Colombia (corresponding to the southern volcanic segment). They found differences suggesting that the calc–alkaline volcanism of Ecuador and that of southern Colombia are different, and that the anomalous enrichment in compatible and incompatible elements in andesites and dacites could be influenced by the structure of deep faults in the continental wedge.

As described in this chapter, the most recent and active volcanism in Colombia is distributed in three segments with differentiable intrinsic characteristics and variations that are linked not only to the conditions of the prevolcanic basement but also to the current complex tectonic configuration of the NW corner of South America, which is not yet well established. These characteristics can be summarized as follows:

- The segments are limited by NW–SE–trending lineaments, some of which coincide with larger structures in the Panamá Basin. These lineaments also limit the gap between the northern and central volcanic segments.
- The distance from the volcanic front to the trench for each volcanic segment varies from south to north from 240 to 310 km. Each segment presents rear–arc volcanism with different characteristics (Monsalve et al., 2020).
- The depth of the oceanic lithosphere under the volcanic front is well defined for the northern volcanic segment. However, 2° to the south, it is not possible to identify the

Benioff zone under the arc due to the sparse intermediate–depth seismicity.

- The volcanic products in the three segments correspond mainly to calc–alkaline andesites and dacites related to subduction. However, each segment has particular geochemical characteristics, which were also observed by López & Zuluaga (2015) and Marín–Cerón et al. (2018). Several of the volcanoes show a transition to an adakitic composition in their most recent products. This pattern is especially evident in the central volcanic segment, as well as in the Azufral Volcano, in the extreme northern part of the southern segment; in the Cerro Machín and Cerro Bravo Volcanoes, in the extreme southern and northern parts of the northern volcanic segment.
- The adakitic tendency of volcanoes in the Northern Andean Volcanic Zone was initially observed in Ecuador (i.e., Bryant et al., 2006 and references therein). Subsequently, this trend was identified in Colombia in the ancient rocks of the Nevado del Ruiz Volcano and in some of the most recently active volcanoes (i.e., Borrero et al., 2009; Correa–Tamayo, 2009). This adakitic signature could have several origins and may not necessarily be related to the original interpretation of slab melting (Defant & Drummond, 1990). Normal magmatic processes in arcs, such as melting and metasomatism of the mantle wedge, assimilation in the lower crust, and fractional crystallization, among others (i.e., Castillo, 2012; Garrison & Davidson, 2003), can produce an adakitic affinity in the resulting igneous rocks. However, the diversity of Colombian volcanism, eruptive styles and volcanic rocks could reflect a variety of processes that must be evaluated, both individually and regionally, considering the particular structural and tectonic context of the volcanic areas.
- Since the eruption of the Nevado del Ruiz Volcano in 1985, knowledge about Colombian volcanism related to the characteristics of recent volcanoes and their behavior has increased through continuous monitoring. However, the relationship between their occurrence and the geological and tectonic evolution of the northern Andes is still unknown.
- The volcanic structures of Pleistocene age, identified to the NE of the Cerro Bravo Volcano, correspond to monogenetic to transitional volcanism, mainly of phreatomagmatic character, different from the volcanism on the cordillera axis. This volcanism could reflect the reactivation of some structures in the Panamá Basin, such as the Sandra Rift (which marks the boundary between the Nazca Plate and the Coiba Block), as suggested by Lonsdale (2005).
- Future volcanic research in Colombia should focus not only on complementing knowledge about the eruptive history of active volcanoes but also on determining the processes involved in the generation of magma at depth and its ascent to the surface. Additionally, future work should strive to better understand the relationship between modern volcanism and the oldest volcanism, which may reveal information on the spatiotemporal evolution of volcanism in relation to the geological evolution of the Colombian territory and the potential associated resources. Moreover, the relationship between the distribution of volcanism and the configuration of the subducting plate must be the subject of deeper and interdisciplinary studies.

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Explanation of Acronyms, Abbreviations, and Symbols:

Am	Amphibole
Bi	Biotite
Carder	Corporación Autónoma Regional de Risaralda
CHEC	Central Hidroeléctrica de Caldas S.A.
Cpx	Clinopyroxene
ENEL	Ente Nazionale per L’energia Elettrica
HREE	Heavy rare earth element
Icel	Instituto Colombiano de Energía Eléctrica
InSAR	Interferometric Synthetic Aperture Radar
ky	Kiloyears
Lg waves	Guided crustal wave traversing large distances along continental paths
Lp	Long–period earthquakes
LREE	Light rare earth element
masl	Meters above sea level
Ol	Olivine
Olade	Organización Latinoamericana de Energía
Opx	Orthopyroxene
OVSM	Observatorio Vulcanológico y Sismológico de Manizales
OVSP	Observatorio Vulcanológico y Sismológico de Pasto
Ox	Oxides
Pg	Plagioclase
Qz	Quartz
SGC	Servicio Geológico Colombiano
VT	Volcanic–tectonic earthquakes

Author’s Biographical Notes

Maria Luisa MONSALVE graduated in geology at the Universidad Nacional de Colombia, obtained a DEA at the University Pierre et Marie Curie, Paris VI, and was a PhD student at the University of Geneva, Switzerland (1988–1990). Her research is focused mainly on physical volcanology, petrology, and volcanic hazard assessment. As part of the SGC, she has been working on the recent volcanism of Colombia and elaboration of volcanic hazard maps. She has also been working in geothermal exploration at the CHEC and as a research associate at the University of Miami. She is currently the coordinator of the Observatorio Vulcanológico y Sismológico de Manizales del SGC.