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Chapter 10

Rear–Arc Small–Volume Basaltic Volcanism in Colombia: Monogenetic Volcanic Fields

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Abstract Small–volume basaltic volcanoes in Colombia are located on the eastern flank of the Central Cordillera and in the Upper Magdalena Valley, in a rear–arc position with respect to the active arc front. These are mainly small volcanoes that form predominantly scoria cones with associated lava flows, pyroclastic rings, and isolated lava flows, which have a composition that varies from highly subsaturated nephelinites, basanites, and alkaline basalts to basalts and subalkaline andesites. In rear–arc position to the segments of the active volcanic front, three main groups are recognized with this type of volcanoes. The first group, located in the south, has been recognized mainly through photogeological studies in Nariño, Putumayo, and Caquetá Departments. From this group, only the nephelinic Sibundoy Volcano (Muchivioy) has been directly studied through field–based geological observations. A second group in the Huila Department has been denominated in the literature with the name of "Alkalibasaltic Volcanic Province", in which three monogenetic volcanic fields are defined: Moscopán, Isnos–San Agustín, and Acevedo, taking into account their geographical position, geochemical characteristics, and structural setting. However, the interaction of the tectonic and structural factors give rise to differences and similarities in the products emitted by these volcanoes, making this volcanic province a clear example of the difficulty of defining a monogenetic volcanic field. In addition, in this group, for the first time four scoria cones with associated lava flows are reported, that were previously known as "Basaltos de Acevedo" of ultramafic character. The third group, called in this work the Metaima Monogenetic Volcanic Field, is located in the Tolima Department and corresponds to basalt and calc–alkaline high–magnesium (Mg# = 65–70) basaltic andesites that may represent primary magmas.

The presence of this volcanism inferred to be related to the complex tectonic configuration of the Andean North Volcanic Zone due to the rupture of the Farallón Plate and the formation of the Panamá Basin in the Miocene. Despite the lack of radiometric dating, this volcanism likely spams an age range from the Pliocene – Pleistocene (?) to the Holocene based on their morphometry, preservation, or stratigraphic considerations. The geomorphology and the preliminary morphometric analysis of the volcanic centers suggest a very recent age for some of them, even with the possibility of having been formed by historical eruptions, according to some reports that should be analyzed in greater detail.

Keywords: *monogenetic volcano, scoria cones, alkaline basalts, Upper Magdalena Valley, Algeciras Fault System.*

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Quaternary Neogene Paleogene Cretaceous Jurassic Triassic Permian Carboniferous Devonian Silurian Ordovician Cambrian Proterozoic

Resumen Los volcanes monogenéticos basálticos en Colombia se encuentran ubicados en el flanco oriental de la cordillera Central y el Valle Superior del Magdalena, en posición de trasarco con respecto al frente activo del arco. Se trata en su mayoría de volcanes pequeños que forman principalmente conos de escoria con flujos de lava asociados, anillos piroclásticos y flujos de lava aislados, que presentan una composición que varía desde nefelinitas altamente subsaturadas, basanitas y basaltos alcalinos hasta basaltos y andesitas subalcalinas. En posición retroarco con respecto a los segmentos volcánicos del frente volcánico activo de Colombia se reconocen tres grupos principales con este tipo de volcanes. El primero, localizado en el sur, ha sido reconocido principalmente mediante estudios fotogeológicos en los departamentos de Nariño, Putumayo y Caquetá. De este grupo solo el volcán nefelinítico de Sibundoy (Muchivioy) se ha estudiado directamente a través de observaciones geológicas de campo. Un segundo grupo en el departamento del Huila ha sido denominado en la literatura con el nombre de "Provincia Volcánica Alcalibasáltica", en la que se definen tres campos volcánicos monogenéticos: Moscopán, Isnos–San Agustín y Acevedo, teniendo en cuenta su posición geográfica, características geoquímicas y control estructural. Sin embargo, la interacción de los factores tectónicos y estructurales da lugar a diferencias y similitudes en los productos emitidos por estos volcanes, haciendo de esta provincia volcánica un claro ejemplo de la dificultad de definir un campo volcánico monogenético. Adicionalmente, en este grupo, se reportan por primera vez cuatro conos de escoria con flujos de lava asociados, conocidos anteriormente como "Basaltos de Acevedo" de carácter ultramáfico. El tercer grupo, denominado en este trabajo Campo Volcánico Monogenético Metaima, está localizado en el departamento del Tolima y corresponde a basaltos y andesitas basálticas calcoalcalinas altas en magnesio (Mg# = 65–70) que pueden representar magmas primarios.

La presencia de este volcanismo monogenético estaría relacionada con la configuración tectónica compleja de la Zona Volcánica Norte de los Andes dada por la ruptura de la Placa de Farallón y la formación de la cuenca de Panamá en el Mioceno. A pesar de la falta de dataciones radiométricas, puede decirse que este volcanismo podría abarcar edades desde el Plioceno–Pleistoceno (?) hasta el Holoceno con base en su morfometría, conservación o consideraciones estratigráficas. La geomorfología y el análisis morfométrico preliminar de los centros volcánicos sugieren una edad muy reciente para algunos de ellos, con la posibilidad de haberse formado por erupciones históricas, según algunos reportes que deben ser analizados con mayor detalle.

Palabras clave: *volcán monogenético, conos de escoria, basaltos alcalinos, Valle Superior del Magdalena, Sistema de Fallas de Algeciras.*

1. Introduction

The monogenetic volcanoes are very common and important manifestations in the Earth´s surface, characterized by eruptions of small volume of magma, generally emitted in simple episodes lasting from days to several years as it has been observed in recent eruptions (Cañón–Tapia, 2016; Connor & Conway, 2000; Németh, 2010; Smith & Németh, 2017; Valentine & Gregg, 2008; Walker, 1993). The study and understanding of the mechanisms and processes that originate them have acquired great importance; the origin and morphology of a monogenetic volcano can be complex and the eruptions that gave rise to them can last longer than expected (Erlund et al., 2010; Németh & Kereszturi, 2015).

The characteristic expression of these volcanic systems are fields enclosing small, dominantly basaltic volcanic "edifices" which are related to different tectonic environments, including intraplate, extensional, and subduction. Volcanic centers within a given field commonly show vent clustering and vent alignments, attesting the control by the underlying structure including faults and the tectonic stress regime (Cañón–Tapia, 2016; Connor & Conway, 2000; Germa et al., 2013; Le Corvec et al., 2013; Mazzarini et al., 2010; Németh, 2010). The magmatic output from these fields can extend in time for up to a few million years and cover large areas in spite the total magma output of the entire volcanic fields rarely exceeding few km^3 (Valentine & Connor, 2015).

Eruption styles of small–volume volcanoes range from magmatic to phreatomagmatic and effusive to explosive. Magmatic eruptions include scoria cones and lava flows, while phreatomagmatic activity is characterized by maars, tuff rings, and tuff cones (e.g., Kereszturi & Németh, 2012; Valentine & Connor, 2015).

Being monogenetic volcanoes the most common type of volcanism on Earth, researches has increased due to the importance in understanding the geotectonic configuration and evolution of the territories where they are located, as well as for the evaluation of the threat and risk that its activity may have on surrounding communities (Bebbington & Cronin, 2011; Bemis & Ferencz, 2017; Smith & Németh, 2017).

In Colombia, the Andes mountain range is divided into three branches, Western, Central, and Eastern Cordilleras (WC, CC, and EC), separated by the inter–Andean valleys of Cauca–Patía and Magdalena Rivers (Figure 1). The Neogene – Quaternary volcanic products of Colombia are found mainly in the CC and WC and the inter–Andean Cauca–Patía valley, continuing towards Ecuador. The active front arc is divided in southern, central, and northern volcanic segments (Monsalve–Bustamante, 2020) and, in the rear–arc position of each segment, in the eastern flank of CC and the inter–Andean Magdalena valley, exist clusters of small–volume basaltic volcanoes (Figure 1).

Alkali basalts in the Upper Magdalena Valley (UMV) in Huila Department (central volcanic segment), as well as basaltic subalkaline andesites, associated to small volcanic cones were initially identified and grouped by Kroonenberg et al. (1982a, 1987) in the "Alkalibasaltic Volcanic Province" (AVP). Small–volume basaltic and basaltic andesitic cones, displaying monogenetic features, have also been identified in the Tolima Department, northern volcanic segment, and in the southern volcanic segment in Nariño–Caquetá–Putumayo region (i.e., Ceballos et al, 1994; Núñez, 2003; Núñez et al., 2001). These volcanoes form rear–arc clusters, located 20–30 km behind of active volcanic front (Figure 1).

In Colombia, this kind of volcanism have been in the focus of volcanology research until recent years (Kroonenberg et al., 1982a, 1987; Murcia et al., 2017; Núñez et al., 2001). The purpose of this chapter is to show the current state of knowledge, providing information about location, morphological features, petrography, and geochemistry, and grouping them into monogenetic fields, in order to discuss their possible origin, from the analysis of the available information.

2. Methodology

The existing information on monogenetic basaltic volcanism in Colombia was compiled and analyzed, complementing it with field recognition, classification of the volcanic structures, and sample of the associated deposits, for future petrographic and geochemical studies. The analysis of shaded relief images and field work led to the identification of new basaltic volcanoes. Morphological measurements of the volcanic structures, as well as the areas covered by the lava flows, were made on the shaded relief images generated in ArcGIS 10.5 with the *Hillshade* tool from P band–GeoSAR radar image, provided by the Instituto Geográfico Augustín Codazzi (IGAC) to the Servicio Geológico Colombiano (SGC). The process involved geological mapping based on interpretation of these images, under GIS software using 3D visualization and analysis tools. Table 1 identifies the volcanoes mentioned throughout this work, including the authors who have reported them.

3. Background

The first references about the existence of volcanoes, eastern of volcanic front of Colombia, is found in Pérez (1862) who mentions the volcano "Patasco" (the geographical description, suggest that it is Patascoy Volcano in Putumayo Department) and, data on other possible volcanoes (i.e., La Fragua) in the area, also indicating very recent volcanic activity in this region (Bureau des longitudes de France, 1824; Ramírez, 1975).

The first review about the existence of basaltic volcanic rocks in the SW of Colombia, around La Cocha Lake (Campanero Hill), is due to Küch (1892), who analyzed petrographically the samples collected by Wilhelm REISS and Alphons STÜBEL, who studied the volcanoes of the Colombian territory between 1868 and 1869.

The first report on the presence of basaltic volcanic rocks, in the area of San Agustín in the UMV, is due to Bergt (1899), who analyzed petrographically a fragment of a statue of the Pre–Columbian Augustinian culture, as well as a pebble from the Guayabo River, finding similarity with the basalts from the Campanero Hill described by Küch (1892).

Tello & Hernández (1976) and Hernández & Tello (1978) identified the first volcanoes in UMV (Table 1). They did not recognize the basaltic character of eruptive products, describing layers of "vitreous–tuff, welded tuffs, and an andesitic flow". The description is closely resembling the textural characteristics of ignimbrites of the Guacacallo Formation, defined by Kroonenberg et al. (1981), on which the basaltic centers are located.

Basaltic volcanism, later to the ignimbritic formation, was reported and described by Kroonenberg & Diederix (1982) and Kroonenberg et al. (1982a), who recognized 13 small eruptive centers (Table 1), including those previously identified by Tello & Hernández (1976) and those from La Argentina and Oporapa–San Roque areas. These authors as well as Diederix & Gómez (1991) describe the volcanoes as highly eroded cones and their products (lava flows and pyroclastic) strongly weathered and altered basalts and basaltic andesites. Additionally, they describe basaltic lavas in other sectors such as Merenberg and Acevedo. The latter was described as a thick lava flow in the basin of the Suaza River.

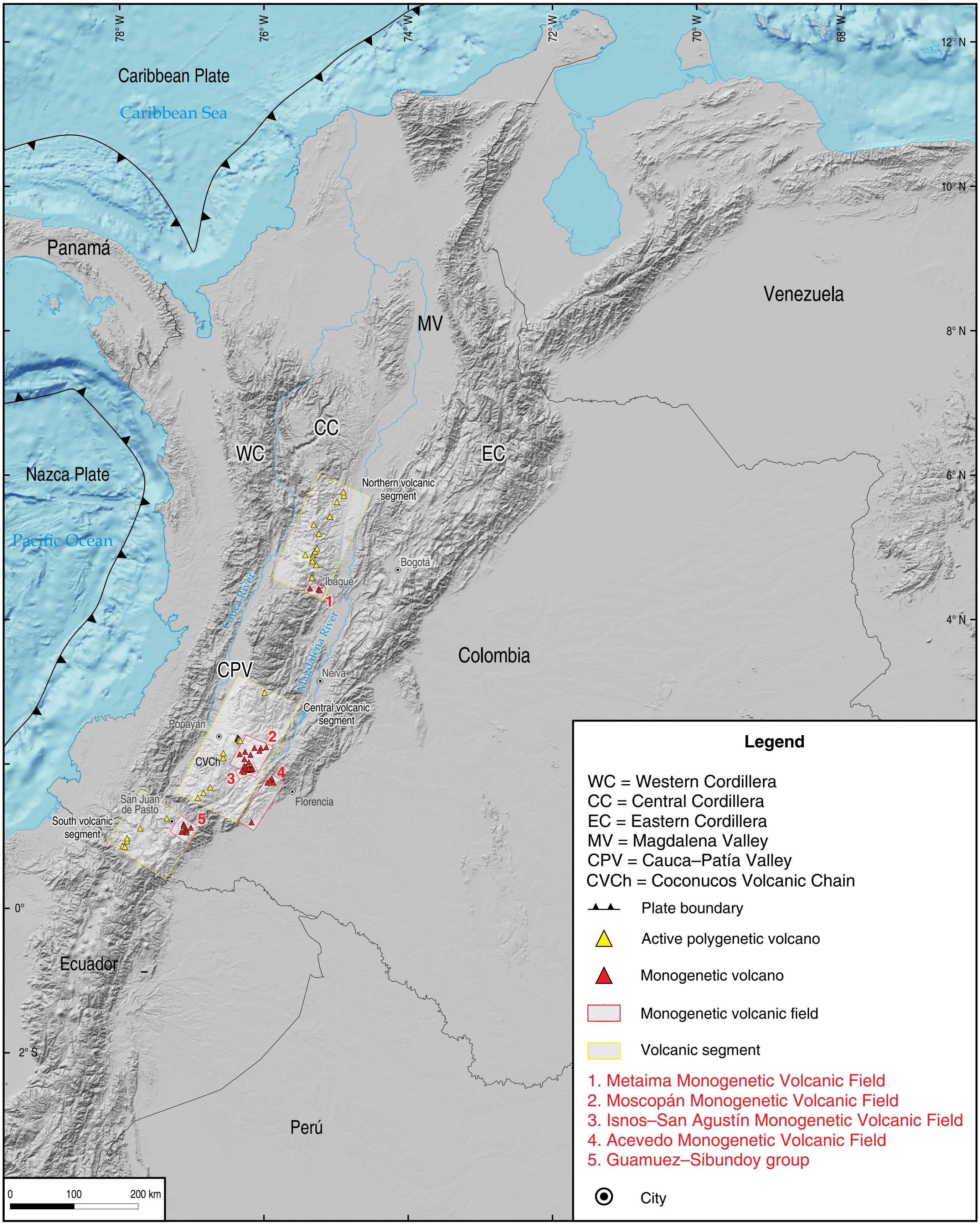

Figure 1. Map of Colombia showing the Quaternary active polygenetic volcanoes and monogenetic volcanic fields the most relevant physiographic features of Colombia.

In addition, Kroonenberg et al. (1982b) identified photogeologically, between the Villalobos and Mandiyaco Rivers to the W of the Caquetá Department, volcanic geoforms and possible lava flows that cause the diversion of the Villalobos River. The degradation and the forest cover did not allow them to confirm the volcanic nature.

West of the Sibundoy valley (4 km SW of Santiago town), there are two basaltic eruptive centers described by Buchelli (1986) and Núñez (2003), as the Sibundoy Volcano. This region was the epicenter of an earthquake on 20 January 1834 and the reports on the earthquake (Ramírez, 1975; Sarabia et al., 2006) present frequent references to the fact that the town of Santiago was "founded on a volcano", and even it is mentioned that the earthquake was due to its eruption. In any case, the descriptions are ambiguous, and it is not possible, with the data provided, to confirm that a volcanic eruption has occurred related or at the same time of the earthquake.

In photogeological studies carried out by Ceballos et al. (1994) and Castañeda et al. (1996), the volcanoes of UMV are grouped in "Cluster 2" and "Huila–Sotará Volcanic Cluster", respectively, and identified the Granates Volcano. Robertson et al. (2002) give the name of "Huila Oriental Volcanic Complex" to this set of volcanoes, and subsequently Flórez (2003) groups them with the name of "La Plata–San Agustín Cluster".

In the Amazonian foothills, south of the town La Fragüita, Ingeominas & Geoestudios (2003) and Núñez (2003) reported the presence of basaltic lavas, which they named "Sabaleta basalts". The unit is exposed near Sabaleta River tributary of the Caquetá River.

Flórez (2003), in a photogeological study, differentiated 8 small volcanic centers east La Cocha Lake, which he called the grupo Guamuez–Sibundoy.

The geological mapping of the UMV was carried out by SGC, between 1998 and 2003. Marquínez et al. (2003a, 2003b) described the lava flow of Santa Leticia and include El Dorado Volcano, which corresponds to the Granates Volcano. The rest of the area was mapped as "Basic volcanic unit" (Cárdenas et al., 2002, 2003; Rodríguez et al., 1998; Velandia et al., 2001a, 2001b) and "Acevedo Basalts" (Ingeominas & Geoestudios, 1998; Rodríguez et al., 2003).

Using the tools of Google Earth, Zuluaga (2011) made preliminary morphometric measurements in the volcanoes located in San Agustín–San José de Isnos area, grouping them under the name of "San Agustín Monogenetic Volcanic Field".

Rodríguez (2017) and Rodríguez & Sánchez (2017) presented a study on El Morro scoriaceous cone.

The field work carried out by SGC in Ibagué surroundings led to the identification of a scoria cones with associated lava deposits, which was called Guacharacos Volcano, and another small pyroclastic ring structure, called Tabor Volcano (Gómez et al., 2016; Núñez et al., 2001), to which a lava flow deposit was recently identified by the authors of this work. Galindo (2012) carries out new studies on the Guacharacos Volcano and Murcia et al. (2017) consider that these structures form a monogenetic volcanic field, which named "Pijao".

Monsalve & Gómez (2015) identify a small structure SE of Cajamarca Town, named Alsacia Volcano that gave rise to a basaltic lava flow on which Regnier (2015) reported geochemical analysis.

4. Description of the Monogenetic Volcanic Regions and Fields

From N to S, the regions of Colombian where it has been reported small–volume basaltic volcanism are: Ibagué–Cajamarca in Tolima Department, UMV in Huila Department, Guamuez–Sibundoy in Nariño, Putumayo, and Caquetá Departments (Figure 1; Table 1).

4.1. Ibagué–Cajamarca

In this region, located on the eastern flank of the CC, S and SE from the southernmost volcanoes of the northern active volcanic segment of Colombia, monogenetic volcanic structures have been identified, named Alsacia, Guacharacos, and Tabor (Gómez et al., 2016; Monsalve & Gómez, 2015; Núñez et al., 2001), the first one is located at 1.5 km SE of Cajamarca town and the others two to the SE of the Ibagué city. These volcanic manifestations are grouped under the name Metaima Monogenetic Volcanic Field (MeMVF) in this work (Figure 2).

The Guacharacos and Tabor Volcanoes are built on the Ibagué Fan, considered Pleistocene in age, and are located in the interception of the Ibagué Fault, that is a NE right lateral strike–slip fault, and Buenos Aires Fault (Figure 3). Both the Ibagué and Buenos Aires Faults show signs of neotectonic activity (Núñez et al., 2001; Osorio et al., 2008). The Alsacia Volcano is associated with an unnamed NE fault that crosses the Cerro Machín Volcano and continues southwards through the Anaime River valley (Mosquera et al., 1982).

The Guacharacos Volcano presents two pyroclastic cones associated with two lava flows (Figures 3, 4a). The first lava flow to the north occupies the valley of the Guacharacos Stream and another to the S that descends the Zanja Honda Stream (Figure 3). They are constituted by basalts–andesites light gray to reddish gray, locally vesiculated, of porphyritic texture with aphanitic groundmass; the olivine phenocrysts are less than 2 mm in length and the vesicles have elongated and irregular shapes. Scoria cone are made of pyroclastic fall deposits of lapilli and blocks (Figure 4b), which reach thickness up to 2 m and when weathering they became clay of intense dark red color.

The Tabor Volcano is a pyroclastic ring (Figures 3, 4c). The products correspond mainly to massive to vesiculate isolated aphanitic lava blocks, which are found in the surface and inner crater, that could correspond to blocks that are detached from

Table 1. Monogenetic volcanoes identified in Colombia. Coordinates refer to the centre point of the volcanoes.

Name	Coordinates		Elevation (masl)	Proponent of the name
	Latitude N	Longitude W		
Metaima Monogenetic Volcanic Field				
1. Tabor	4° 23’ 55”	75° 10’ 37”	1000	Gómez et al. (2016)
2. Guacharacos	4° 24’ 28”	75° 11’ 26”	1100	Núñez et al. (2001)
3. La Alsacia	4° 25’ 53”	75° 25’ 12”	2115	Proposed in this chapter
Moscopán Monogenetic Volcanic Field				
4. La Palma	2° 18’ 08”	75° 58’ 03”	1711	Velandia et al. (2001a)
5. Santa Leticia	2° 13’ 50”	76° 09’ 52”	2322	Marquínez et al. (2003b)
6. Merenberg	2° 12’ 37”	76° 07’ 33”	2467	Kroonenberg et al. (1981)
7. Tálaga	2° 12’ 02”	76° 06’ 52”	2344	Proposed in this chapter
8. El Morro	2° 11’ 28”	76° 02’ 07”	1852	Kroonenberg et al. (1982a)
9. Marsella	2° 11’ 00”	76° 04’ 19”	2092	Proposed in this chapter
10. El Pensil	2° 10’ 43”	76° 04’ 29”	2054	Kroonenberg et al. (1982a)
Isnos–San Agustín Monogenetic Volcanic Field				
11. Granates	2° 06’ 40”	76° 13’ 01”	2168	Castañeda et al. (1986)
12. Morelia	2° 06’ 08”	76° 17’ 27”	2550	Proposed in this chapter
13. Vega Chiquita	2° 03’ 09”	76° 11’ 07”	1878	Proposed in this chapter
14. San Vicente	1° 59’ 50”	76° 14’ 34”	2283	Proposed in this chapter
15. Yarumal	1° 59’ 07”	76° 13’ 01”	2078	Proposed in this chapter
16. Hornitos	1° 58’ 12”	76° 15’ 36”	2130	Proposed in this chapter
17. Junín	1° 57’ 41”	76° 15’ 10”	2098	Tello & Hernández (1976)
18. Mondeyal	1° 56’ 22”	76° 10’ 31”	1840	Proposed in this chapter
19. San Lorenzo	1° 55’ 43”	76° 11’ 23”	1882	Proposed in this chapter
20. La Horqueta	1° 55’ 29”	76° 14’ 52”	1888	Tello & Hernández (1976)
21. Canastos	1° 55’ 17”	76° 12’ 13”	1864	Proposed in this chapter
22. Purutal	1° 54’ 55”	76° 17’ 53”	1956	Tello & Hernández (1976)
23. Los Ídolos	1° 54’ 53”	76° 14’ 17”	1802	Tello & Hernández (1976)
24. El Trébol	1° 54’ 39”	76° 12’ 39”	1877	Proposed in this chapter
25. La Pelota	1° 54’ 32”	76° 17’ 10”	1909	Tello & Hernández (1976)
26. La China	1° 54’ 09”	76° 18’ 55”	1993	Zuluaga (2011)
27. La Guaca	1° 54’ 02”	76° 14’ 33”	1843	Proposed in this chapter
28. La Gorda	1° 53’ 58”	76° 12’ 39”	1890	Proposed in this chapter
29. Granada	1° 53’ 52”	76° 14’ 52”	1839	Proposed in this chapter
30. Chico	1° 53’ 37”	76° 12’ 30”	1804	Zuluaga (2011)
31. Campoalegre	1° 53’ 45”	76° 10’ 52”	1833	Proposed in this chapter
Acevedo Monogenetic Volcanic Field				
32. La Estrella	1° 45’ 30”’	75° 54’ 27”	1677	Proposed in this chapter
33. Rosario	1° 45’ 25”	75° 55’ 11”	1624	Proposed in this chapter
34. San Marcos	1° 43’ 40”	75° 58’ 24”	1377	Proposed in this chapter
35. La Barniza	1° 43’ 00”	75° 56’ 06”	1768	Proposed in this chapter
36. Sabaletas				
Guamuez-Sibundoy group				
37. Sibundoy (Muchivioy)	1° 07’ 00”	77° 00’ 46’’	2423	Buchelli (1986)

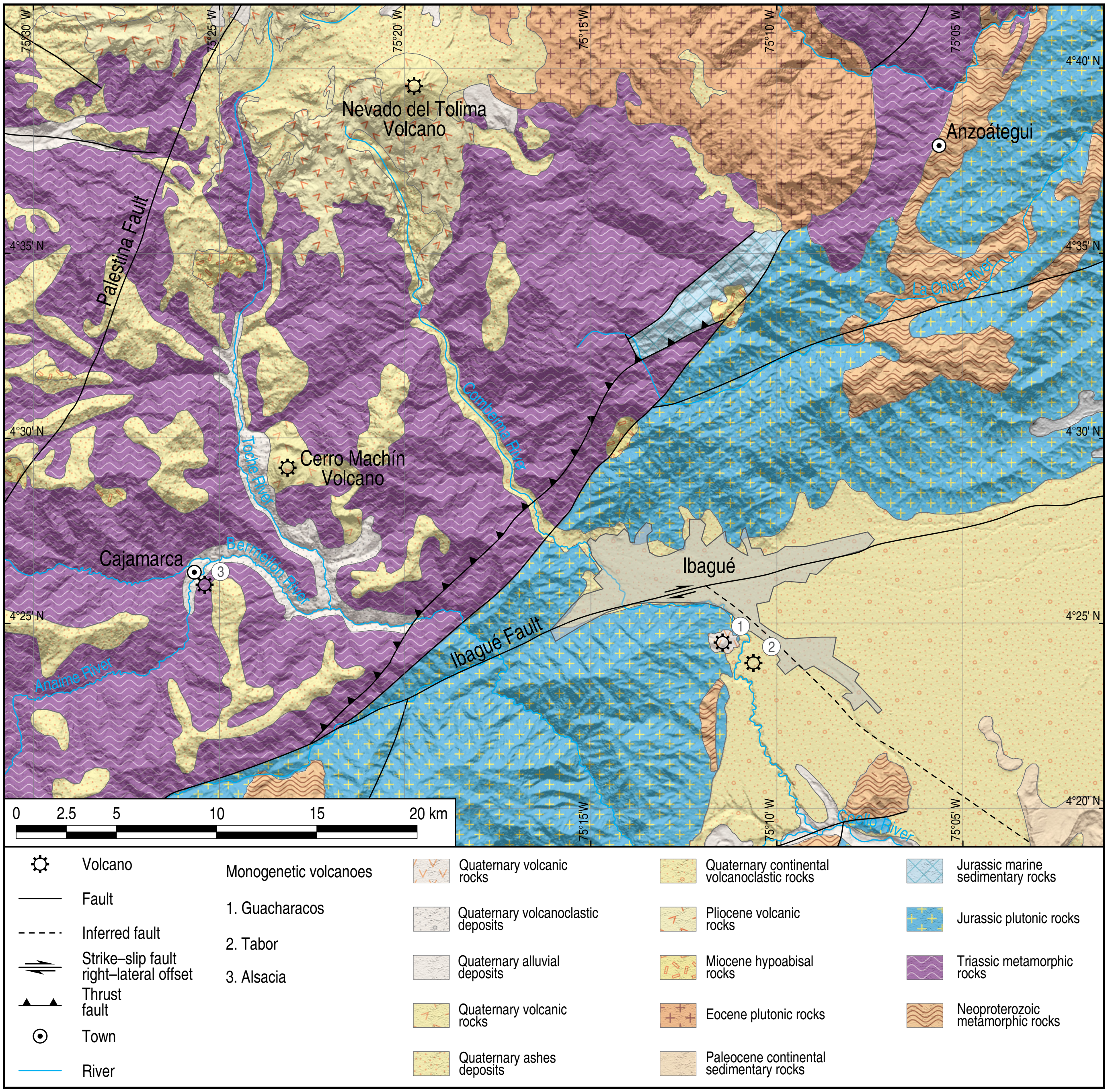

Figure 2. Geological map of Ibagué–Cajamarca region showing the geological setting of the MeMVF. The numbers correspond to the volcanoes in Table 1. Simplified from Gómez et al. (2015).

pyroclastic layers that form the ring. At the surface a thin layer of slightly vesiculated lithic lapilli is recognized. From this volcano emerge a deposit of lava flow in W direction, towards the Combeima River, it is gray color massive, with thickness greater than 10 m, exhibiting porphyritic to aphanitic texture, with olivine phenocrystals.

Due to its morphology and stratigraphic position, with respect to the Ibagué Fan, the volcanism in this sector is considered recent. The Volcanoes of Guacharacos and Tabor are clearly later than this fan. In the Guacharacos Stream, the northern flow of the Guacharacos Volcano can be seen above the conglomerates of the Ibagué Fan (Núñez et al., 2001). It is not discarded the presence of other volcanoes in the area and under the fan.

The Alsacia Volcano corresponds to a scoria cone (Figure 4d, 4e) built on the flank of a metamorphic massif (Cajamarca Complex). It has associated a 1 km long, lava flow deposit, massive to clastogenic on the front, gray to reddish in color, with olivine phenocrystals. It is locally covered by pyroclastic

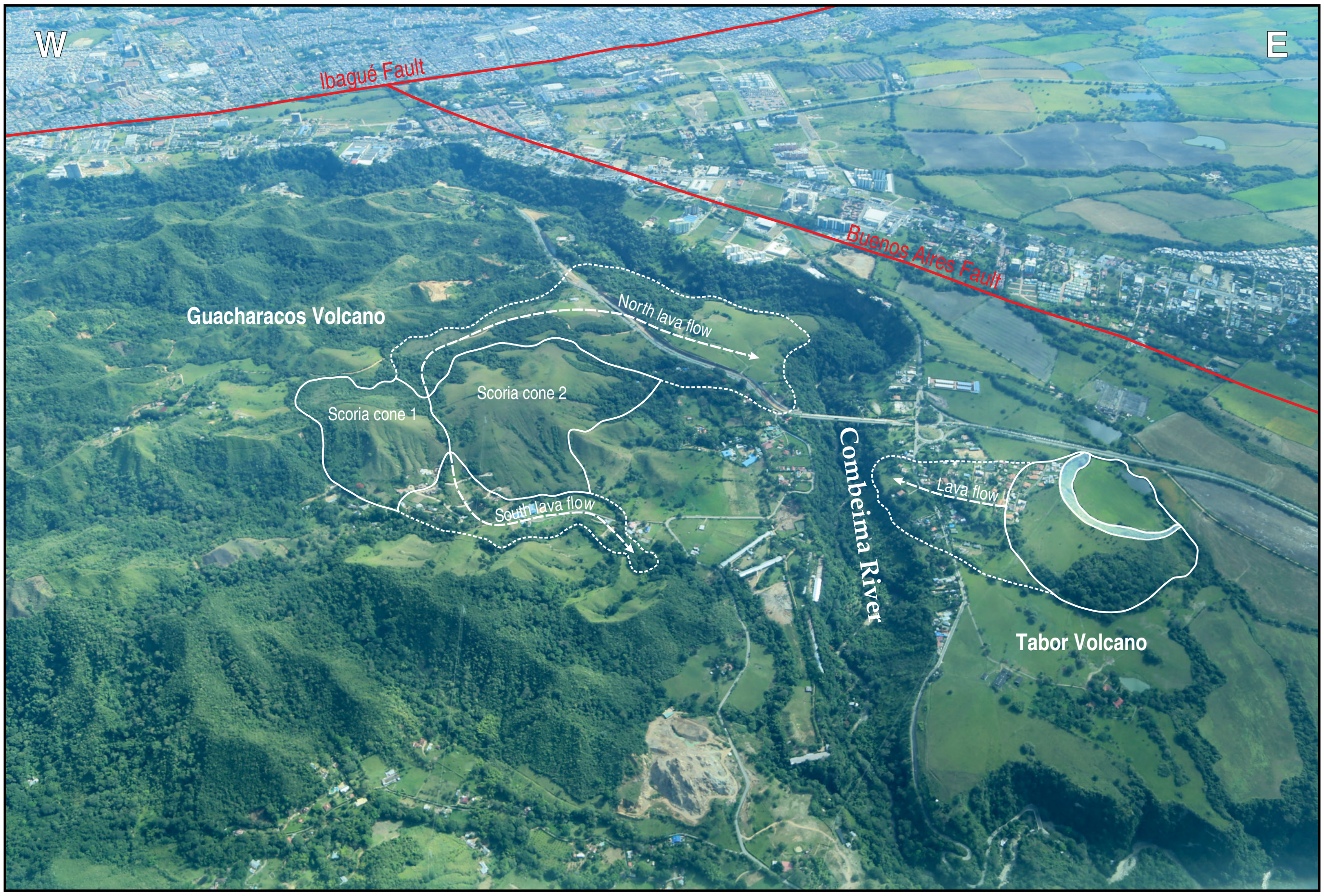

Figure 3. Aerial view of the Guacharacos and Tabor Volcanoes. Arrows indicate the direction of the lava flow. Guacharacos Volcano has two scoria cones and two lava flows, north and south. Tabor Volcano has an open crater towards the NNE and a lava flow towards the W. Note the proximity with the Ibagué and Buenos Aires Faults. Picture courtesy of Forest Engineer César Augusto GUTIÉRREZ.

fall deposits from the Cerro Machín Volcano dated in 5000 y BP (Méndez, 2000).

4.2. Upper Magdalena Valley (UMV)

This group of volcanoes is subdivided, in this work, into three monogenetic volcanic fields: Moscopán (MMVF), Isnos–San Agustín (ISMVF), and Acevedo (AMVF), taking into account their geographical position and other aspects such as structural control and geochemical signature (Figure 5). This group is in rear–arc position to the central volcanic segment.

The volcanoes of the MMVF are aligned NW–SE, parallel to the Coconucos Volcanic Chain (CVCh) (Figure 1); it is included La Palma (Figure 6a) —corresponding to 3 adjacent vents—, Santa Leticia (Figure 6b), Merenberg (Figure 6c), El Morro (Figure 6d), Marsella (Figure 6e), Tálaga, and Pensil Volcanoes. The volcanic edifices, mostly pyroclastic cones with asociated lavas, are built on Jurassic and Permian intrusive igneous rocks and ignimbrites of the Neogene Guacacallo Formation (Marquínez et al., 2003a, 2003b; Rodríguez et al., 1998; Rodríguez et al., 2017; Velandia et al., 2001a).

In this subgroup, La Palma and El Morro eruptive centers stand out for their characteristic scoria cones (Figure 6a, 6d); La Palma has two lava flows, 600–700 meters in length, which descend toward La Plata River; they are massive in the central part and scoriaceous toward the edges, constituted by microcrystalline rocks of porphyritic texture with aphanitic groundmass. The pyroclastic deposits correspond to surge and fall deposits, composed of reddish to grayish scoriaceous lapilli and, to a lesser extent, bombs up to 10 cm in diameter (Figure 7a, 7b). La Palma pyroclastic sequence contains fragments of volcanites of the Guacacallo and Saldaña Formations.

The Merenberg, Santa Leticia, Tálaga, and Marsella Volcanoes have associated lava flows up to 3.5 km in length. The composition is basaltic andesite of aphanitic texture to slightly porphyritic, of gray color, with olivine phenocrysts. In addition, the flows deposits are massive to scoriaceos and often exhibit spheroidal weathering. The Pensil is a pyroclastic ring, with an associated lava flow.

In the central part, behind the CVCh, Sotará Volcanic Complex (SVC), and Sucubún Volcano, the ISMVF is located, containing the largest number of monogenetic volcanoes. These

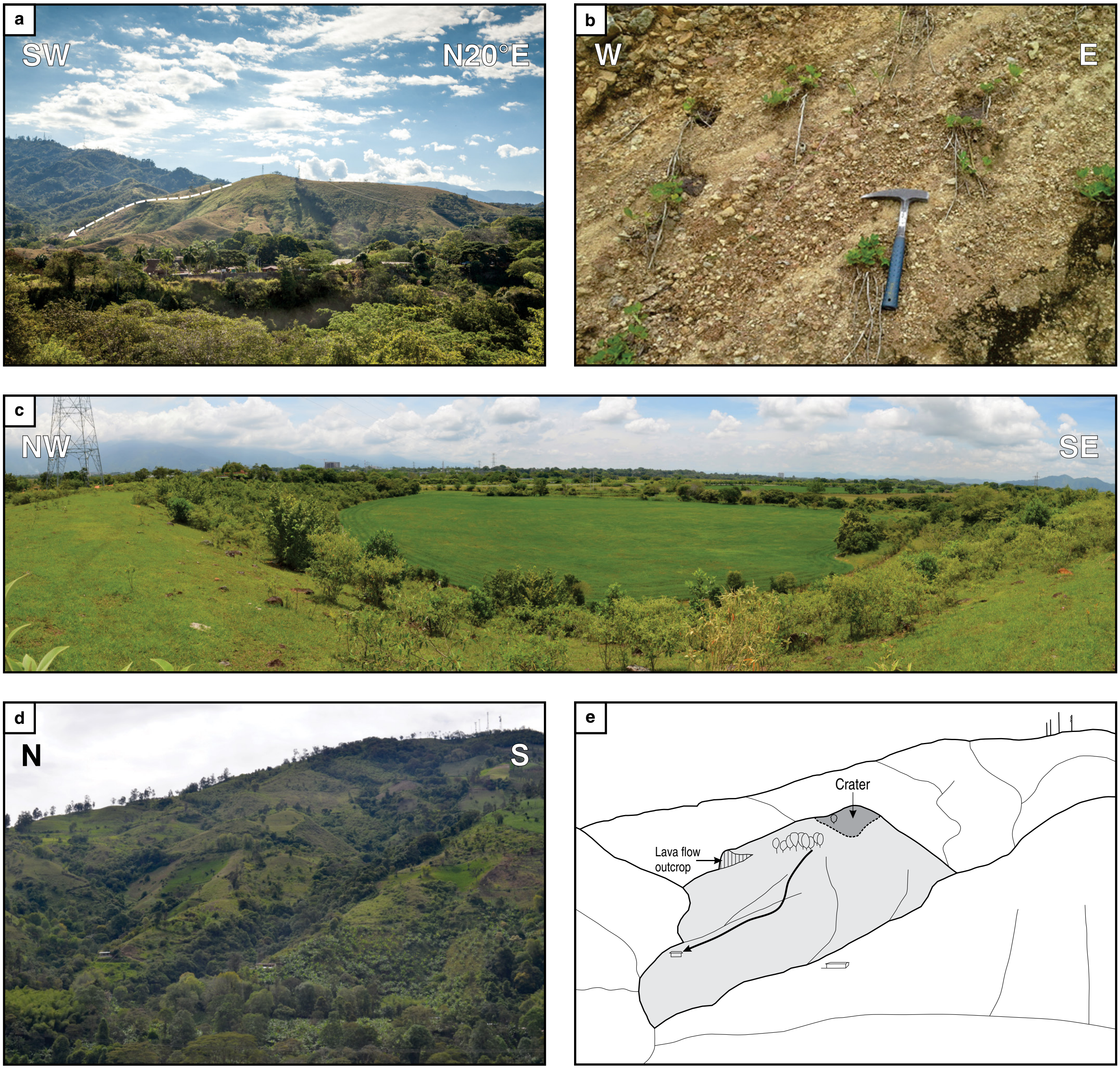

Figure 4. (a) Panoramic view of the Guacharacos Volcano in 2017 from the E, on the Ibagué–Rovira road. The arrow shows the direction of the south lava flow. **(b)** Pyroclastic deposit on the south flank of the Guacharacos Volcano. **(c)** Panoramic view of the Tabor Volcano crater seen from the southwestern edge in 2016. Note that inside the crater there is a rice crop. **(d)** Panoramic view of Alsacia Volcano in 2016, from Cajamarca–Anaime road. **(e)** Simplified sketch showing the volcanic edifice. The arrow shows the direction of the lava flow.

volcanos are: Granates (Figure 8a), Morelia, Vega Chiquita (Figure 8b), San Vicente (Figure 8c), Yarumal (Figure 8d), Hornitos (Figure 8e), Junín (Figure 8f), Mondeyal, San Lorenzo (Figure 9a), La Horqueta (Figure 9b), Canastos (Figure 9c), Purutal (Figure 9d), Los Ídolos (Figure 9e), El Trébol (Figure 9f), La Pelota (Figure 10a), La China (Figure 10b), La Guaca (Figure 10c), La Gorda (Figure 10d), Granada, Chico (Figure 10e), and Campoalegre (Figure 10f). The volcanoes lie on the Guacacayo Formation, whose morphological expression is that of a plateau with undulated morphology (Figure 11a), which is dissected, at some points, up to 400 m by the main rivers such as Magdalena, Bordones, Granates, and Mazamorras (Kroonenberg et al., 1981). The volcanic Guacacallo Formation covers diverse igneous, metamorphic, and sedimentary units, with ages between the Paleozoic and the Miocene (Figure 5).

In general, the volcanic products associated with these volcanoes are lava flow and pyroclastic fall deposits that varies in grain size between lapilli, ash, and bombs, the first two predominating.

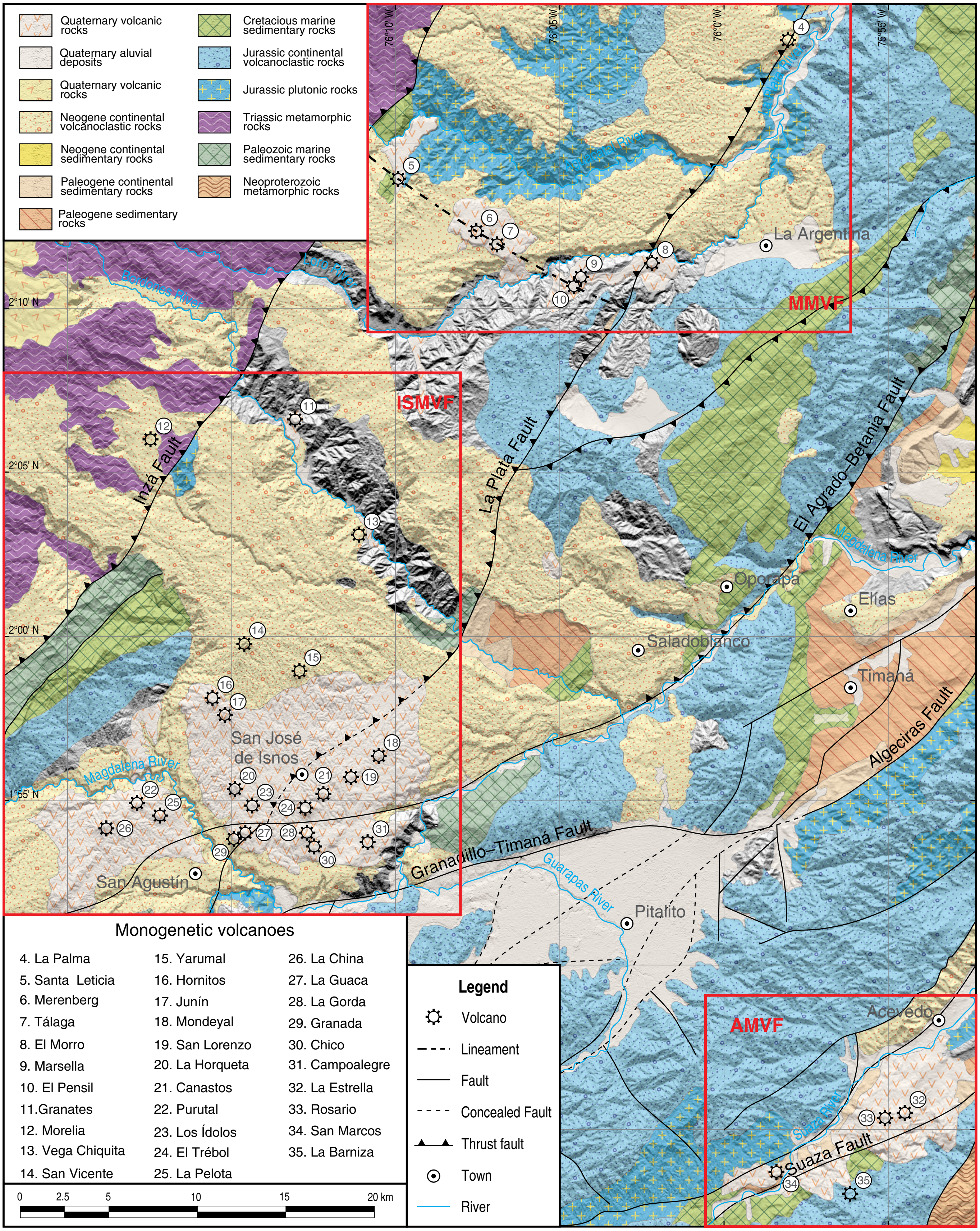

Figure 5. Geological map and location of the volcanoes of UMV, Huila Deparment. The numbers correspond to the volcanoes in Table 1. Simplified from Gómez et al. (2015). (MMVF) Moscopán Monogenetic Volcanic Field, (ISMVF) Isnos–San Agustín Monogenetic Volcanic Field, (AMVF) Acevedo Monogenetic Volcanic Field.

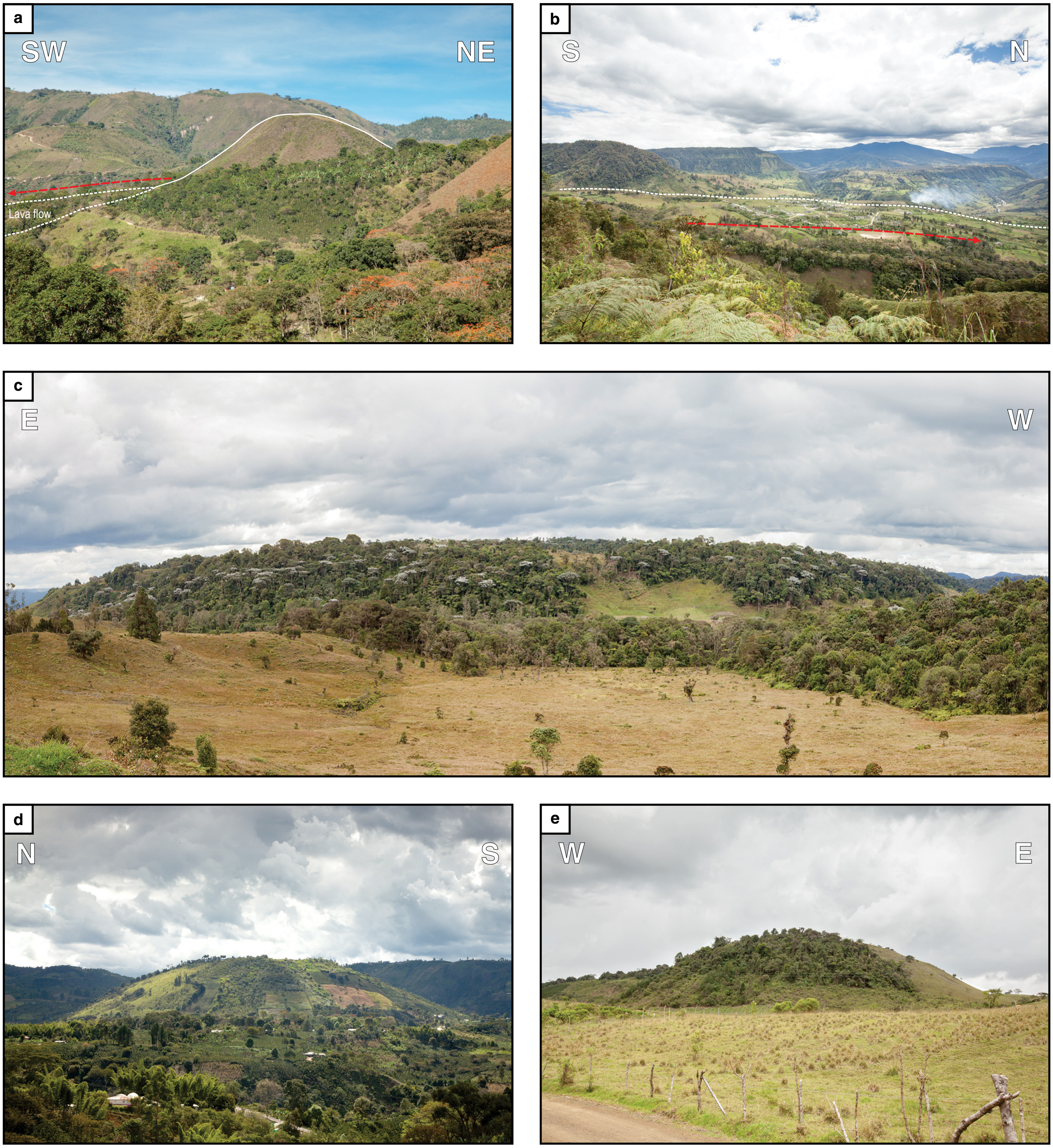

Figure 6. Volcanoes of the MMVF. **(a)** Panoramic view of La Palma Volcano. **(b)** Panoramic view of the Santa Leticia Volcano lava flow. Red arrow shows the direction of the flow. **(c)** Panoramic view of the Merenberg Volcano on the Belén–Santa Leticia–Popayán road. **(d)** Panoramic view of El Morro scoria cone on La Argentina–El Pensil road. Notice the well preserved morphology, indicating its recent age. **(e)** Marsella Volano on El Pensil–Marsella Vereda road.

The lavas are massive scoriaceous and those associated with the Mondeyal Volcano correspond to amygdaloidal and vesicular basalts (Figure 11b, 11c). The best outcrops of pyroclastic deposits are found on the SW flank of La Gorda Volcano and in the SW part of La China, consisting of sequences of scoriaceous lapilli (Figure 11d, 11e), with sporadic bombs, lying on lava flows.

In some localities, lava flows were observed but the source could not be determined. This is the case of the lavas to the

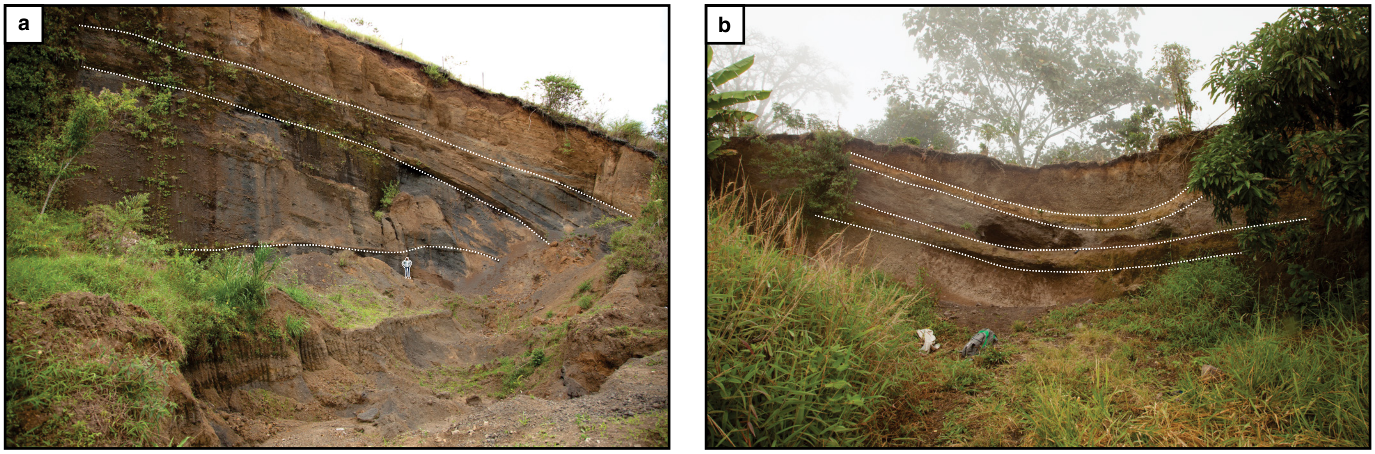

Figure 7. (a) Pyroclastic deposits from the cone of El Morro Volcano on La Argentina–El Pensil road. At least 4 main pyroclastic units are observed, indicating changes in the intensity of the eruption. **(b)** Pyroclastic deposits associated with one of the eruptive centers of La Palma Volcano on La Plata–Guineal–Vereda La Palma road. At least 3 main units of scoriaceous pyroclastics deposits separated by thiner and hardy ash–lapilli levels.

north of the San Agustín Archaeological Park that outcrop along the San Agustín–Archaeological Park–Saldaña road.

The AMVF, previously known as Basaltos de Acevedo (Ingeominas & Geoestudios, 1998; Kroonenberg et al., 1982b; 1987; Rodríguez et al., 2003), is located in the valley of the Suaza River and comprises the volcanoes and products (lavas and pyroclasts) identified in this work. The existence of at least four small volcanoes is confirmed (Figure 12; Table 1), whose products lie discordant on igneous geological units of the Jurassic and sedimentary geological units of the Cretaceous and Paleogene (Ingeominas & Geoestudios, 1998; Rodríguez et al., 2003). These volcanoes are Rosario (Figure 12a), La Estrella (Figure 12b), San Marcos (Figure 12c), and La Barniza (Figure 12d).

The largest volcano within this field, and possibly the oldest of those identified, is La Barniza, situated in the locality of the same name. A lava flow of more than 3 km in length is associated to this volcano; the pyroclastic deposits (lapilli and bombs) are very weathered, becoming red clay material where ceramic remains were found. The other volcanoes: San Marcos, La Estrella, and Rosario are well preserved morphology scoria cones with deposits of lava flows. In the field work, blocks of columnar basalts (Figure 12e) and highly altered red pyroclastic deposits were identified, mainly in the San Marcos Volcano (Figure 12f).

4.3. Putumayo and Caquetá Region

Ingeominas & Geoestudios (2003) described the Basalts of Sabaleta in a small hill 25 m high and an area of 6 km^2. Columnar basalts were identified in outcrop at Sabaleta River (Figure 13). In this work, the Sabaletas Volcano is preliminary included within the AMVF given the lack of petrographic and geochemical characterization. Sabaletas Volcano is located on the Borde Amazónico Thrust Fault in a zone of compressive regime (Figure 14). Sabaletas Volcano is not deformed by the fault and possibly indicates a Pliocene – Quaternary extensionally release.

The volcanic geoforms, between the Mandiyaco and Villalobos Rivers, reported by Kroonenberg et al. (1982b) belong to this region. In the serranía de la Fragua, the Bureau des longitudes de France (1824) and Ramírez (1975) indicate a historical eruption in La Fragua Volcano.

4.4. Guamuez–Sibundoy Region

It is located in rear–arc positon of the southern volcanic segment. To the west of the Sibundoy valley (4 km SW of the town of Santiago) there are two adjacent eruptive centers, which emitted scoriaceous basaltic products, both lava flows and pyroclastic material (bombs of various shapes and sizes, lapilli, and ashes), which cover small alluvial fans. In this sense, Buchelli (1986) and Núñez (2003) consider these volcanic manifestations as Holocene; these authors also report the existence of thermal springs with temperatures between 30 and 76 °C in the surrounding area.

The rocks that make up the lava flows are dark red to dark gray, generally very vesiculated, classified as basalts (Núñez, 2003; Rodríguez & González, 2004). Pyroclasts are dark red in color and form layers of varying thickness; some of these deposits are interpreted as explosion breccias (Núñez, 2003). Duque–Trujillo et al. (2016) highlight the presence of a "hummocky" morphology, consisting of numerous small mounds that they consider a "debris avalanche" produced by a flank collapse.

These volcanic structures, named Sibundoy Volcano by Buchelli (1986) and known as Muchivioy Volcano by the inhabitants of the region, belongs to the volcanic geoforms called by Flórez (2003) grupo Guamuez–Sibundoy (Figure 15).

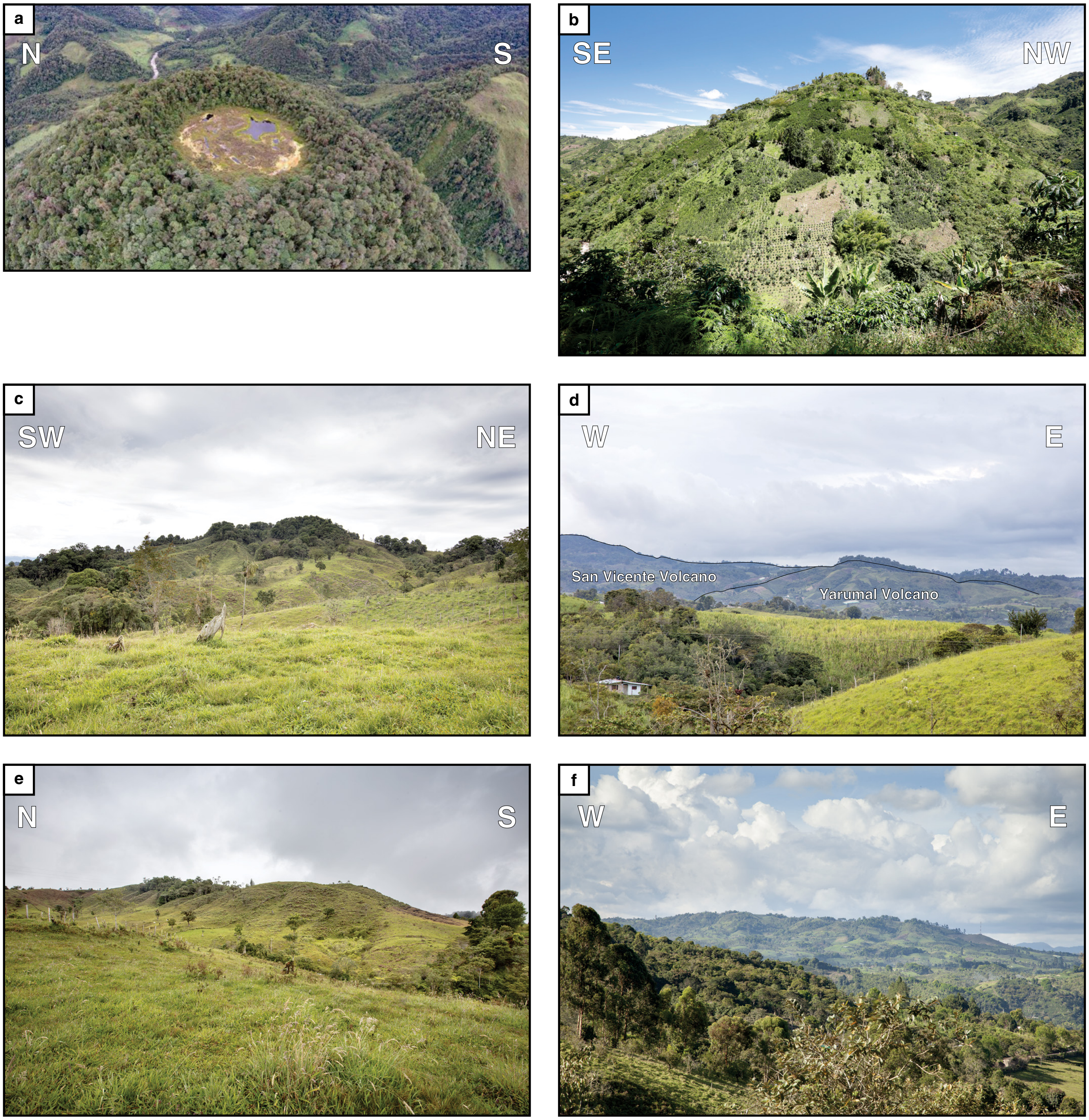

Figure 8. Part 1 of the volcanoes of the ISMVF. **(a)** Aerial view of the crater of the Granates Volcano in Saladoblanco, Huila. Note the lake in the crater. Picture taken from https://www.diariodelhuila.com/huila-con-nuevo-parque-natural-regional. **(b)** Panoramic view of the Vega Chiquita Volcano on the Saladoblanco–Morelia road in Saladoblanco, Huila. **(c)** Panoramic view of San Vicente Volcano on the Vereda San Vicente–vereda Yarumal road in San José de Isnos, Huila. **(d)** Panoramic view of the San Vicente Volcano to the left and Yarumal Volcano to the center on the San José de Isnos–vereda Alto Mondeyal road in San José de Isnos, Huila. **(e)** Panoramic view of Hornitos Volcano on the vereda Hornitos–vereda Alto Junín road in San José de Isnos, Huila. **(f)** Panoramic view of Junín Volcano from south on the San Agustín–veredas El Tablón and Purutal in San Agustín, Huila.

5. Tectonic Setting

In the NW corner of South America, where Andean North Volcanic Zone (ANVZ) is located, the Nazca, South America, and Caribbean Plates interact with the Panamá and North Andean Blocks. The configuration, not well defined, of the Panamá Basin from the Miocene rupture of the Farallón Plate, together with the evolution of the Galápagos Province contribute to the

Figure 9. Part 2 of the volcanoes of the ISMVF. **(a)** Panorámic view of the San Lorenzo Volcano from the SW on the San José de Isnos–vereda Canastos road in San José de Isnos, Huila. **(b)** Scoria cone with horseshoe morphology of La Horqueta Volcano from vereda Las Guacas in San José de Isnos, Huila. **(c)** Panoramic view of the Canastos Volcano on the San José de Isnos–vereda Alto Mondeyal in San José de Isnos, Huila. **(d)** Panoramic view of the Purutal Volcano from S on the San Agustín–veredas El Tablón and Purutal road. **(e)** Scoria cone with horseshoe morphology of Los Ídolos Volcano from vereda Las Guacas in San José de Isnos, Huila. **(f)** El Trébol Volcano from the vereda La Marquesa school in San José de Isnos, Huila.

tectonic complexity of this sector of the South American territory (i.e., Londsdale, 2005; Lonsdale & Klitgord, 1978; Pennington, 1981; Sallares & Charvis, 2003).

Based on bathymetric and magnetic studies of Hey (1977) and Lonsdale & Klitgord (1978), the first models of the tectonic evolution of the Panamá Basin were obtained.

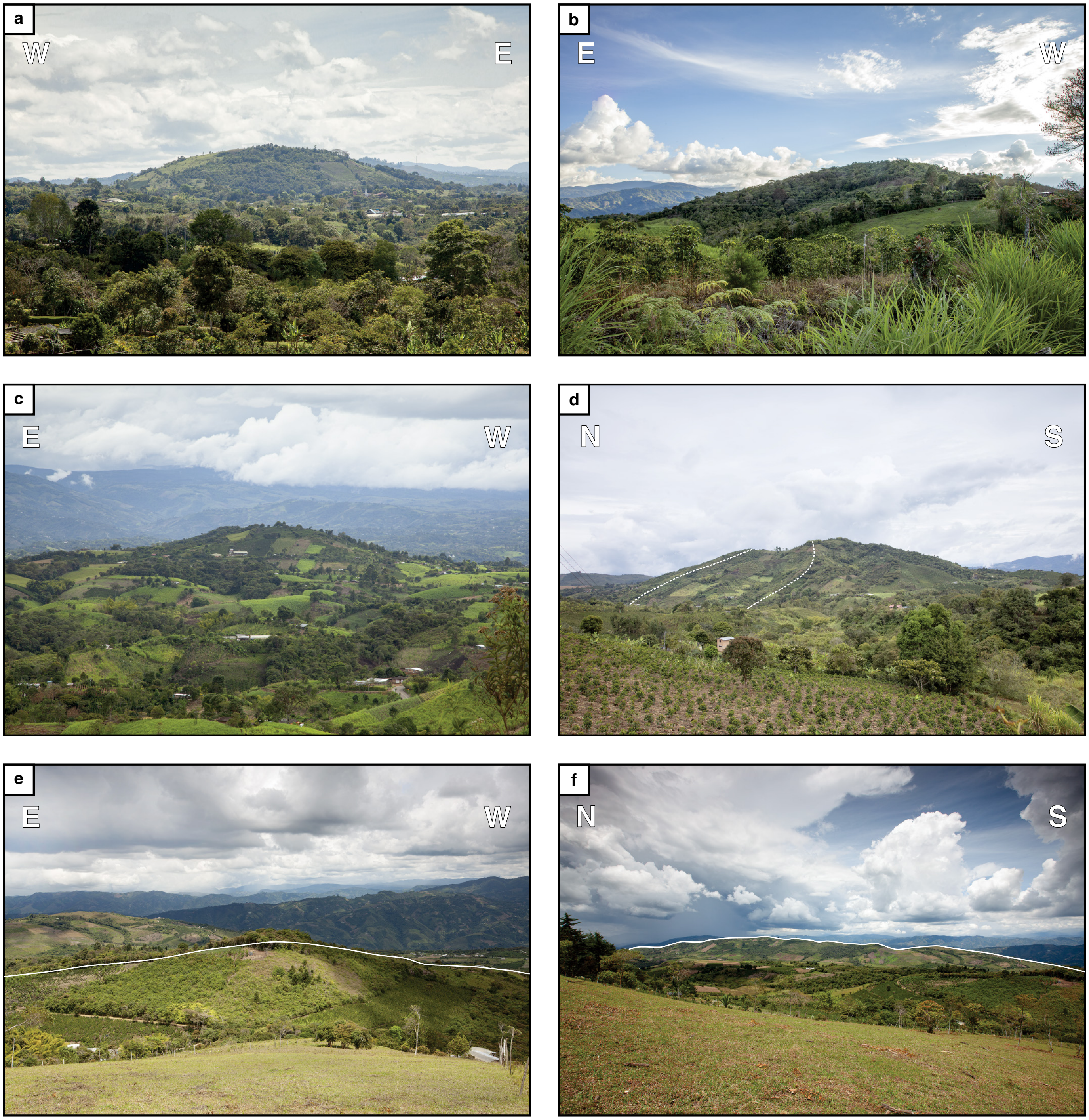

Figure 10. Part 3 of the volcanoes of the ISMVF. **(a)** Panoramic view of La Pelota Volcano from the Parque Arqueológico de San Agustín. **(b)** Panoramic view of La China Volcano on the San Agustín–veredas Purutal and Saldaña road. **(c)** Panoramic view of La Guaca Volcano from the top of El Trébol Volcano. **(d)** Panoramic view of La Gorda Volcano from NW, vereda La Primavera. **(e)** Panoramic view of the Chico Volcano from south flank of La Gorda Volcano. **(f)** Campoalegre Volcano from the south of La Gorda Volcano.

With the interpretation of seismicity and focal mechanisms solutions in the ANVZ, Pennington (1981) defined three tectonic segments that he named Bucaramanga, Cauca, and Ecuador in the north of South America. For the Cauca segment, where the angle of inclination of the subducting plate is 35º, it indicates a normal and continuous subduction, to which the active volcanism of Colombia is associated. The author draws attention to the scarce seismicity, both superficial and intermediate and deep, between 2° N and 2° S. The first is explained by the rupture produced by the 1906 and 1979 earthquakes in the trench (Esmer-

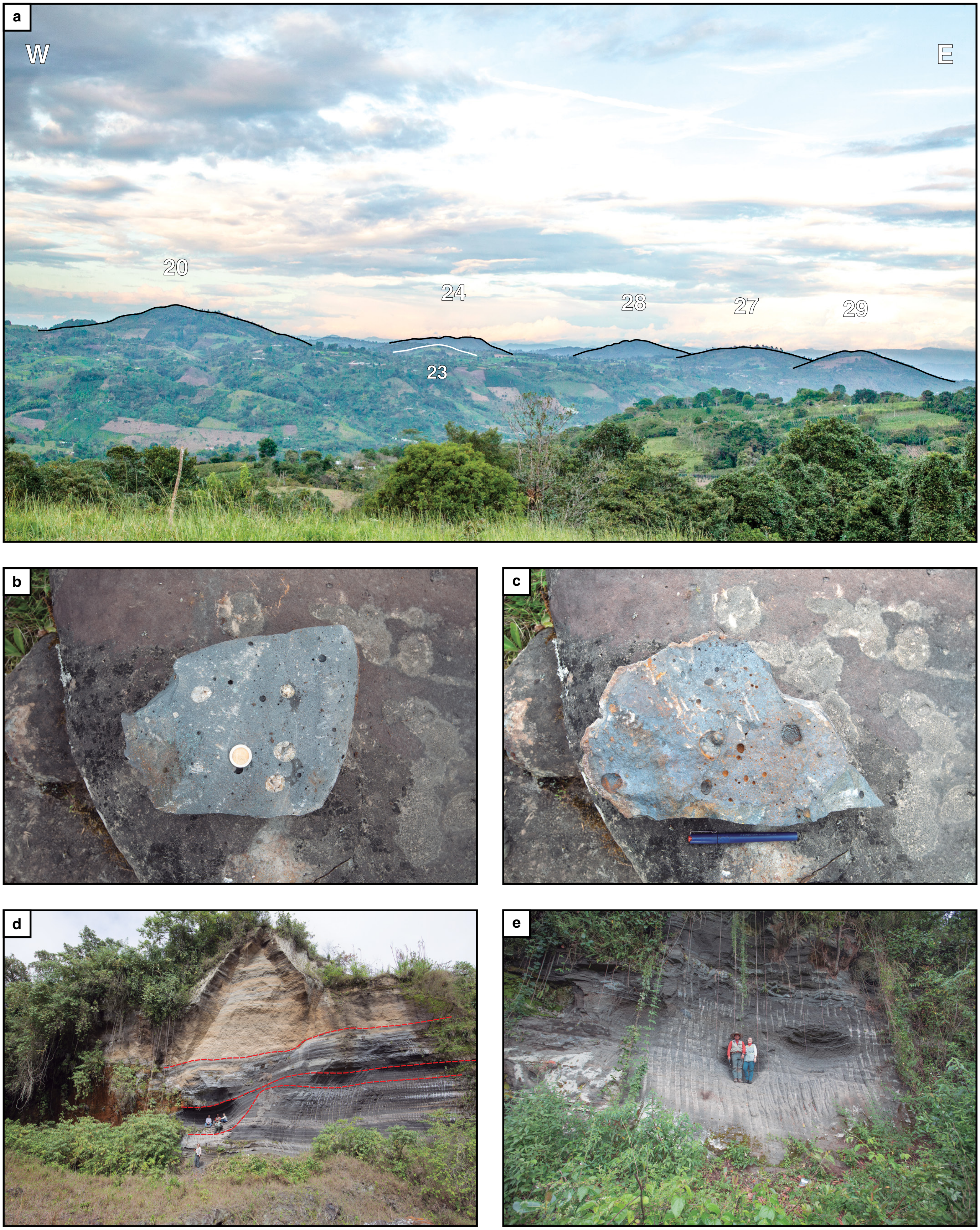
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Figure 11. ISMVF. **(a)** Panoramic view of the ignimbritic plain and the monogenetic volcanoes built on it, from San Agustín Archaeological Park. From left to right: (20) La Horqueta, (23) Los Ídolos, (24) El Trébol, (28) La Gorda, (27) La Guaca, and (29) Granada. The numbers correspond to the volcanoes in Table 1. **(b), (c)** Amygdaloidal and vesicular basalts of the Mondeyal Volcano. **(d)** Pyroclastic sequence of La Gorda Volcano, La Primavera sector. Notice the layers of scoriaceous lapilli, three main units separated by erosional contacts are observed. These units are above a black lava flow. **(e)** Scoriaceous pyroclastic deposits from La China Volcano on the San Agustín–Quinchana road. The sequence are transitional; toward the middle part the layers are hardened.

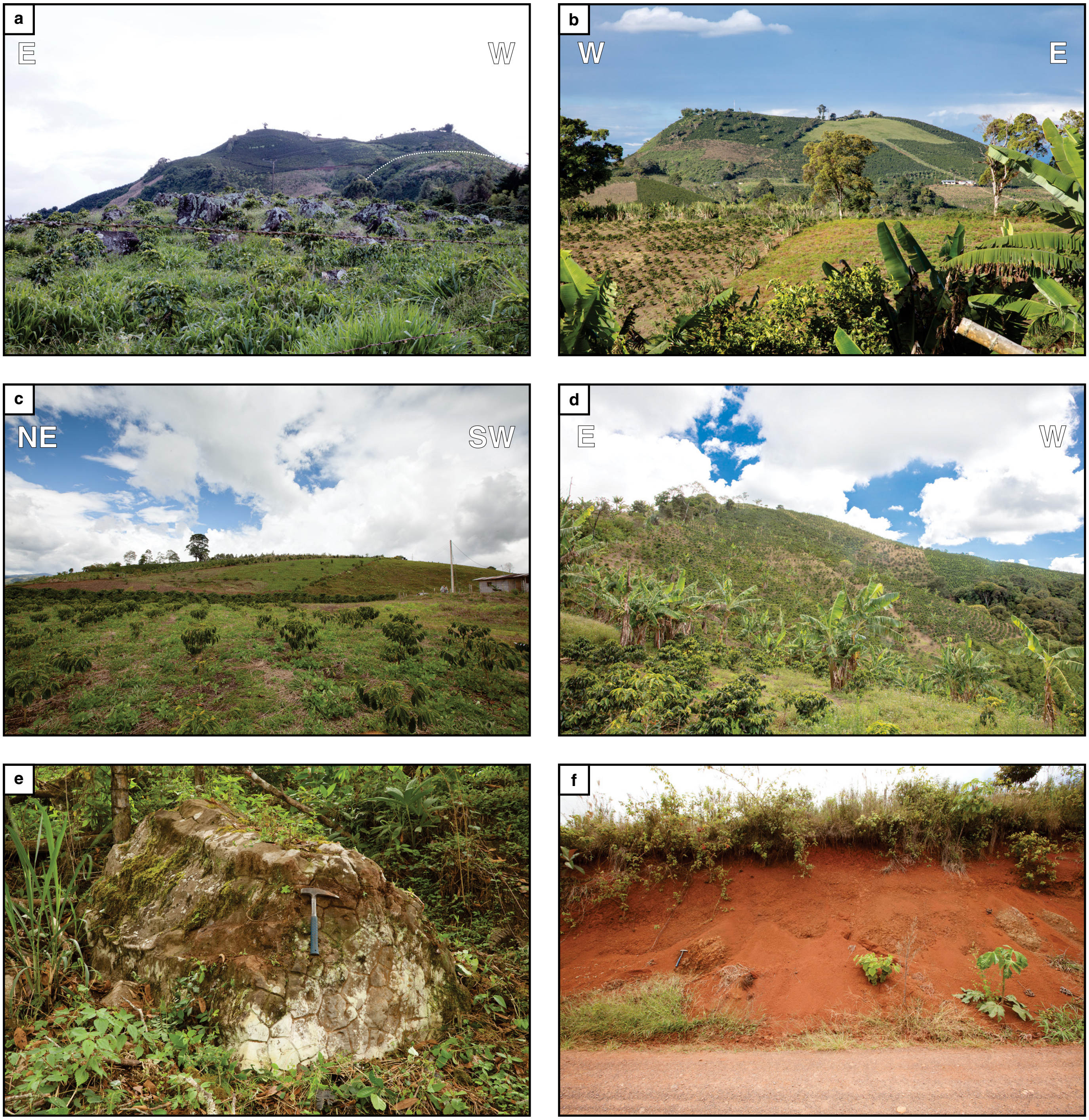

Figure 12. AMVF. **(a)** Panoramic view of La Estrella Volcano with its lava flow in blocks (left) and Rosario Volcano (right, white line) from S on the Rosario–Acevedo road. **(b)** Panoramic view of La Estrella Volcano. **(c)** Panoramic view of the San Marcos Volcano from W on the San Marcos–vereda Versalles–vereda Laureles road. **(d)** View of La Barniza Volcano. **(e)** Basaltic columnar–jointed lava block of the San Marcos Volcano on the Acevedo–San Marcos–San Adolfo road. **(f)** Pyroclastic deposits (lapilli and bombs) of the San Marcos Volcano on the San Marcos–vereda Versalles–vereda Laureles road.

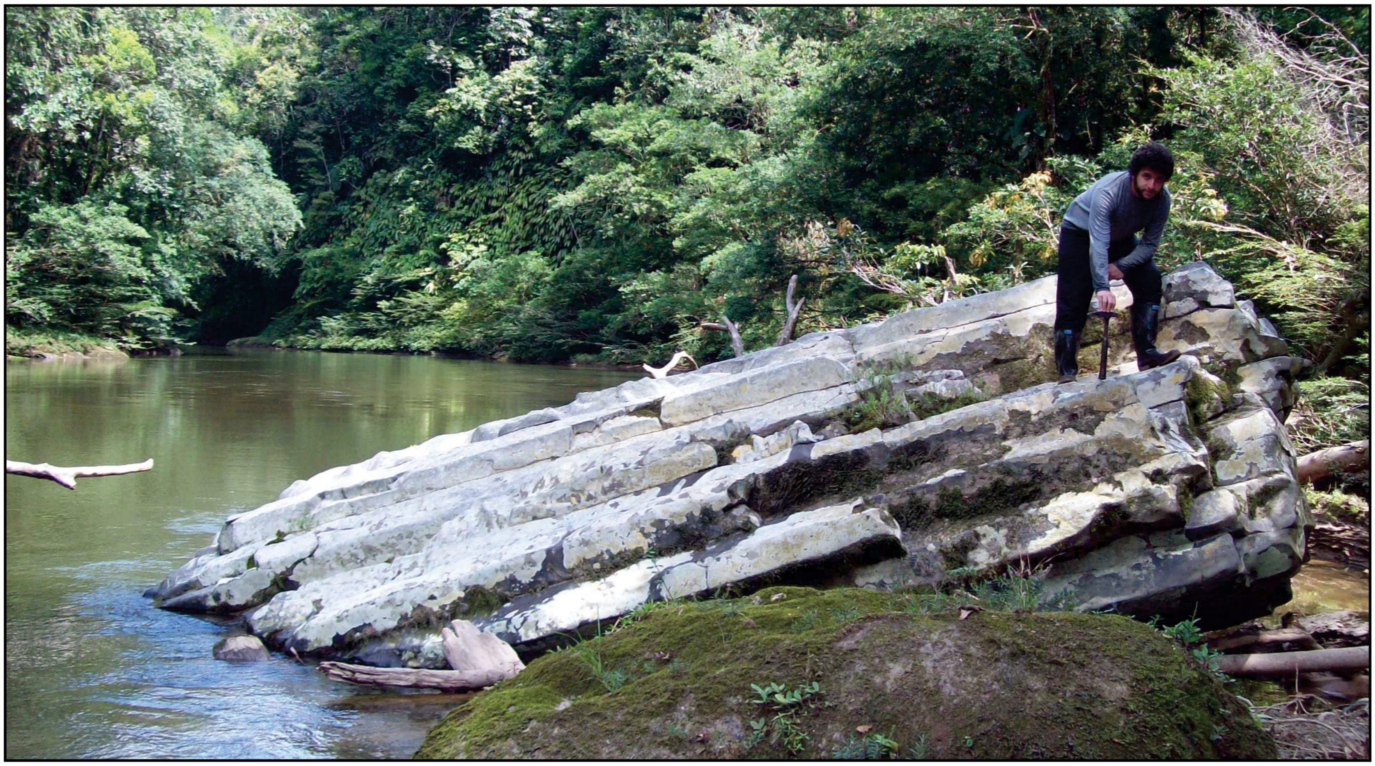

Figure 13. Basaltic columnar–jointed lava block of the Sabaletas Volcano in Sabaleta River. Photographies courtesy of geologist Adrian PÉREZ ÁVILA of the Servicio Geológico Colombiano.

aldas and Tumaco earthquakes). For the others, it proposes that the aseismic region between the Cauca and Ecuador segments is the result of the separation of plates along an area of subduced and now extinct expansion centers —the Malpelo Rift— active until 8 Ma (Lonsdale & Klitgord, 1978). The Ecuador segment dips 35° to N35°E and could be contributing some lithospheric material to N of Ecuador and S of Colombia (Pennington, 1981).

Both Pennington (1981) and Gutscher et al. (1999) consider that this fossil rift is responsible for the separation of the Cauca and Ecuador segments, facilitating the subduction of hot young oceanic crust, which quickly loses the necessary resistance to generate earthquakes. Gutscher et al. (1999) then propose a tectonic segmentation between 2.5° N and 1° S, as well as a lithospheric tear, north of the Carnegie Ridge along the Malpelo Rift fossil spreading center assuming, furthermore, that Carnegie Ridge extends more than 110 km NE, possibly 500 km below the continent (Figure 16). On the other hand, with this hypothesis, they support the adakitic signature of the magmas in Ecuador (Monzier et al., 1997).

The existence of the Andean Block, proposed by Pennington (1981), would be the result of the Carnegie Ridge collision with the Colombo–Ecuatorian trench, and named the limit the "Fault Zone of the Andean Eastern Front", which is transpressive in nature. This fault zone was recognized and named by Velandia et al. (2005), to the SW of the country as Algeciras Fault System, which constitutes the current limit along the northern Andes, starting in the Gulf of Guayaquil in Ecuador and continuing in Colombia and Venezuela. Kellog et al. (1985), interpret the tectonics of the region considering the existence of the North Andean and Panamá Blocks or microplates.

Most of the volcanoes in the MMVF are associated with a NW lineament; to the east, El Morro Volcano is located at the intersection of this lineament with La Plata thrust fault and the volcanoes that make up La Palma are associated with the latter. The ISMVF is associated with a bend to the west of the right–lateral fault with a reverse component of El Agrado–Betania and with the intersection of this fault with La Plata Fault (Figure 5). Diederix et al. (2020a) considers El Agrado–Betania Fault as part of the Algeciras Fault System.

Associated with pull apart basins to the Algeciras Fault System, we have associated the AMVF and Guamez–Sibundoy group (Figure 17). These two fields are found on the bend and towards the west of the Algeciras right lateral strike–slip fault. The presence of these monogenetic fields in these transtentional systems indicates interaction with the mantle.

Buenaventura Rift is another expansion center at 3º 40' N, of the E Panamá Basin, extinct around 12 Ma, which was identified by Hardy (1991), based on the interpretation of magnetic data. Other segments of the Malpelo Rift were recognized by Lonsdale (2005), suggesting that the Yaquina Graben originated as a transtensional transform valley, proposing, from satellite information, that it culminates joining another extinct expansion segment, around 3.38° N, slightly south of the extinct Buenaventura Rift.

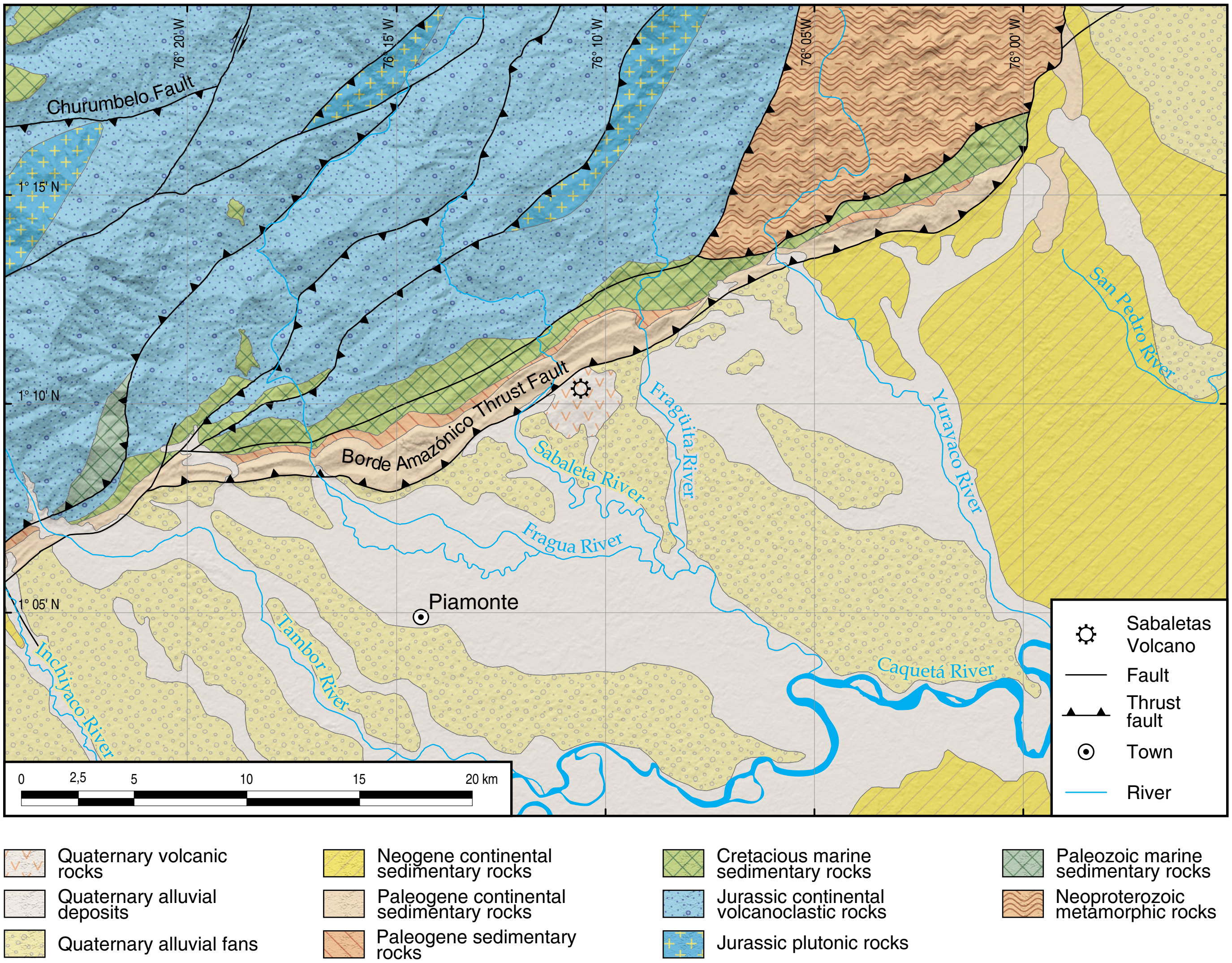

Figure 14. Geological map and location of the Sabaletas Volcano in Caquetá Deparment. Simplified from Gómez et al. (2015).

Arcila & Dimaté (2005), present a section perpendicular to the trench, including topographic, gravity (Bouguer anomaly total), estimates of the depth of the Moho by inversion of gravity anomalies and distribution of well–established seismicity with depth. In general, the analyzed information allows to define a continental crust thickness of about 30 km and a plate subducting under the western Colombia, which reaches a depth of about 70 km under the WC, but it is no possible to follow it further east (Figure 18).

With measurements of SKS phase and slab–related local S splitting at 38 seismic stations, Idárraga–García et al. (2016) interpreted the delay times of the two phases to show that most of the SKS splitting is due to entrained mantle flow beneath the subducting Nazca and Caribbean slabs. The authors detected a change in the SKS phase splitting pattern ca 2.8° N, which they related to variation in the geometry of the subduction, marked by the presence of a lithosphere–scale tearing structure that they named "Malpelo Tear", taking up Lonsdale & Klitgord (1978), Gutscher (1999), and Lonsdale (2005), whom describing it as a wide anomalous zone, oriented NW–SE, located between ca. 3.8° N and ca. 2.5° N, where it reaches the Pacific coast of Colombia. Furthermore, Idárraga–García et al. (2016) interpreted that in this region, NE–SW oriented SKS phase fast directions are consistent with the general dip direction of the underthrusting of the Carnegie Ridge beneath South America.

6. Morphometry of the Monogenetic Volcanoes

A morphometric analysis of the volcanoes of the Metaima, Moscopán, Isnos–San Agustín, and Acevedo Monogenetic Volcanic Fields was carried out as shown in Figures 1, 19. The analyzed volcanoes correspond to scoria cones (i.e., El Morro, Marsella, Canastos, Purutal, La Guaca, Granada, and Rosario) and, some of them have associated lava flow deposits (Guacharacos, Alsacia, Granates, Junín, La Horqueta, El Trébol, La Gorda, Chico, La Estrella, San Marcos, and La Barniza); two have pyroclastic rims morphology and also have associated lava

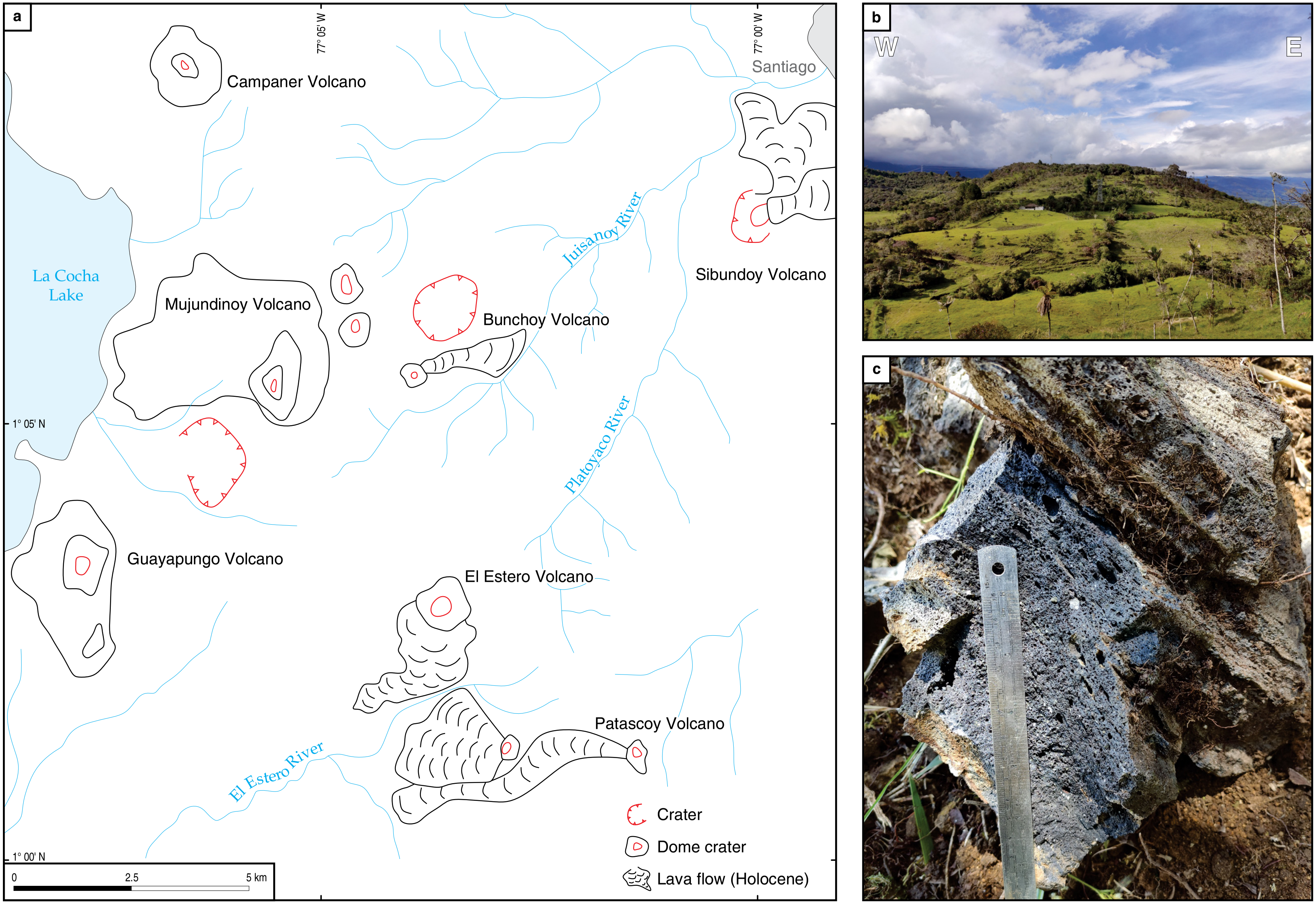

Figure 15. (a) Location of the group Guamuez–Sibundoy volcanoes, photogeologically identified by Ceballos et al. (1994), Robertson et al. (2002), Flórez (2003). Modified from Flórez (2003). **(b)** South flank of Muchivioy Volcano. **(c)** Scoriaceous lava of Muchivioy Volcano. Photographies courtesy of Víctor Camilo RIVERA, SGC research assistant.

deposits (Tabor and El Pensil). Visual observation shows that the vast majority of cones are well preserved and only in some have drainage developed (i.e., Guacharacos, Merenberg, El Pensil, Yarumal, Hornitos, La Horqueta, Los Ídolos, El Trébol, and Campoalegre). The Junín and Campoalegre Volcanoes are elongated (Figures 8f, 10f) and Junín has three associated lava flows.

Bemis & Ferencz (2017) pointed out that numerous scoria cones are asymmetric, ellipsoidal, with off–center or incomplete craters and proposed seven types of shapes, that they obtained from observations of the morphology from scoria cones in Guatemala and Salvador volcanic fields as follows: (i) Ideal, (ii) gully, (iii) horseshoe, (iv) tilted, (v) crater row, (vi) amorphous, and (vii) parasitic. With this proposal, the cones of the volcanoes referenced here were analyzed and cataloged as shown in Table 2.

On the other hand, the morphometric studies to classify the shapes of the scoria cones, take into account parameters such as height (Hco) and basal diameter (Dco) of the cone, diameter (Dcr) and depth (Pcr) of the crater and inclination of the cone among others. With these measurements, various relationships are obtained, especially the Hco/Dco and Dcr/Dco ratios, which with the angle of inclination of the cone, are used as indicators of the relative age and erosion of the volcanic edifice (i.e., Bemis, 1995; Bemis & Ferencz, 2017; Hasenaka & Carmichael, 1985; Dohrenwend et al., 1986; Pike & Clow, 1981; Porter, 1972; Wood, 1980). These calculations were made for the UMV volcanoes and the results are shown in Table 2.

In general, the height of the volcanic structures varies between 43 m (San Marcos, Figure 12c) and 141 m (Campoalegre, Figure 10f); the diameter of the base fluctuates between 532 m (Marsella, Figure 6e) and 1568 m (El Trébol, Figure 9f). Some of them do not have a visible crater and others have a closed crater (Granada; La Pelota, Figure 10a; Canastos, Figure 9c) or open (La Horqueta, Figure 9b and La Gorda, Figure 10d), with a diameter between 40 m (Mondeyal) and 770 m (El Pensil) and depth between 9 m (Canastos, Figure 9c) and 84 m (La Gorda, Figure 10d). The steepest cone belongs to the Granates Volcano (56°) and the lowest to Hornitos (13°).

In a group of scoria cones, the oldest are generally considered to be more eroded, having lower Hco/Dco ratios, while the slopes of the younger cones are greater than the slopes of the older cones. On the other hand, the Dcr/Dco ratio is lower for the more degraded than for the more recent ones (i.e., Dohrenwend et al., 1986; Porter, 1972; Wood, 1980).

When using these criteria for the UMV cones, it is found that with the Hco/Dco coefficient La Estrella, Granada, La Horqueta, La Pelota, Purutal, and Campoalegre Volcanoes would be the most recent, while the oldest would be San Marcos, Yarumal, Rosario, Los Ídolos, and El Trébol. Taking into account the inclination of the slopes of the cone, the newest would be Granates, which even has a lake in its crater (Figure 8a), El Morro, Marsella, and La Estrella and the oldest Hornitos, La Gorda, Chico, Yarumal, and Mondeyal. Finally, with the Dcr/Dco relationship, the most degraded are Mondeyal and La China and the least are Yarumal, La Horqueta and Los Ídolos. The analysis and detail of these relationships is relatively consistent with the field observations, but they must be analyzed in detail with a geological detailed mapping.

7. Petrography of the Monogenetic Volcanic Fields

In this section, both the information known to date and new data from basaltic rock samples from the volcanoes recognized in the different regions is compiled. Tables 3 and 4 describe the mineralogy and classification of samples of some volcanoes of Metaima and San Agustín–Isnos Monogenetic Fields.

The samples from the volcanoes of the Metaima Monogenetic Field are gray to reddish fine porphyritic to aphanitic rocks, slightly vesiculated, and locally scoriaceous. Some vesicles are filled with oxides and carbonates. Petrographically, the samples correspond to andesitic basalts with olivine and pigeonite and olivine basalts with pyroxene (Galindo, 2012; Leal–Mejía, 2011; Núñez et al., 2001; Regnier, 2015).

The Guacharacos lavas exhibit porphyritic texture, consisting of phenocrystals (20–30 %) of olivine as the predominant mafic mineral and clinopyroxene to a lesser extent, included in a microcrystalline to intergranular matrix (70–80 %), with a fluid texture, sometimes vesiculated composed of tabular plagioclase, clinopyroxene, volcanic glass, and magnetite in less quantity; some samples from this volcano (Leal–Mejía, 2011), as well as that of Alsacia Volcano, contain sporadic olivine in the matrix. The vesicles are generally irregular and elongated. Galindo (2012) reports a quartz xenolite with a crown of fine–sized pyroxene crystals.

Guacharacos' lavas present inclusions or vesicles filled by secondary alteration minerals. Figure 20 shows petrographic images taking with a scanning electron microscope (SEM). Figure 20a depicts the general appearance of a rock sample from the Guacharacos Volcano, and Figure 20b shows one of the inclusions contained in the lava that present a texture that visibly contrasts with texture of the basalt. It corresponds to a dissolution texture of mortar type, with two different gray tons that the EDS spectrum suggests amorphous silica for the dark phase and a brighter phase containing iron, magnesium, and calcium. The inclusions observed are interpreted as vesicles that may be filled by a mixture of epidote, chlorite, and amorphous silica. Irregular vesicles are interpreted as a dissolution effect given their texture and the general alignment they present (Cortés, 2017).

SEM analyses of samples from the Guacharacos Volcano (Cortés, 2017) show that olivine phenocrysts are zoned, with core crystals relatively richer in the forsteritic molecule than the crystals rims. Clinopyroxene occurs as individual crystals or as aggregates, showing weak zonation (Figure 20a).

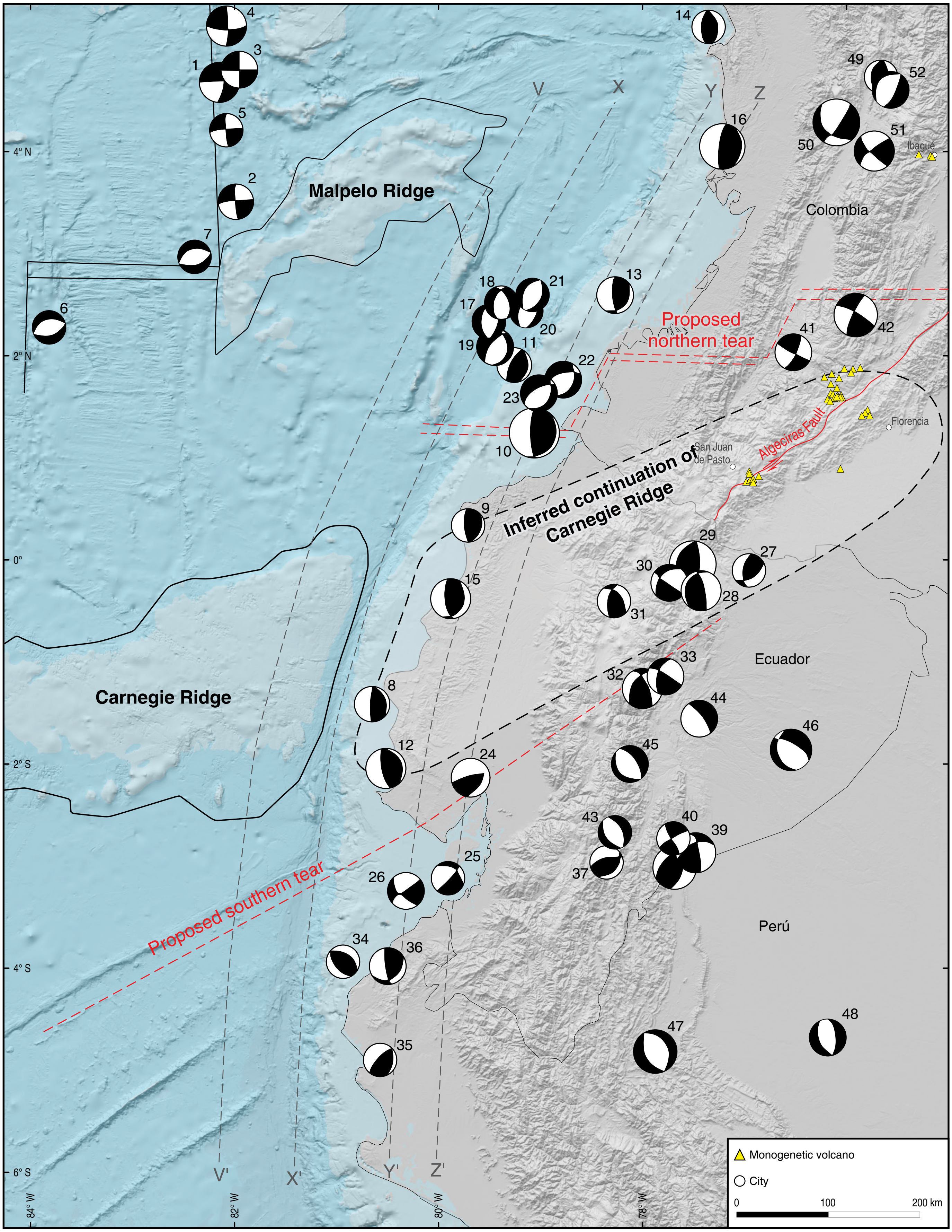
Malpelo Ridge
Carnegie Ridge
Colombia
Ecuador
Perú
Proposed northern tear
Proposed southern tear
Inferred continuation of Carnegie Ridge
Algeciras Fault
San Juan de Pasto
Florencia
Ibagué
V
X
Y
Z
V'
X'
Y'
Z'
4° N
2° N
0°
2° S
4° S
6° S
84° W
82° W
80° W
78° W
Monogenetic volcano
City
0
100
200 km

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Figure 16. Tectonic configuration of the E Panamá Basin (Modified from Gutscher et al., 1999). Notice the inferred continuation of Carnegie Ridge under South American Plate.

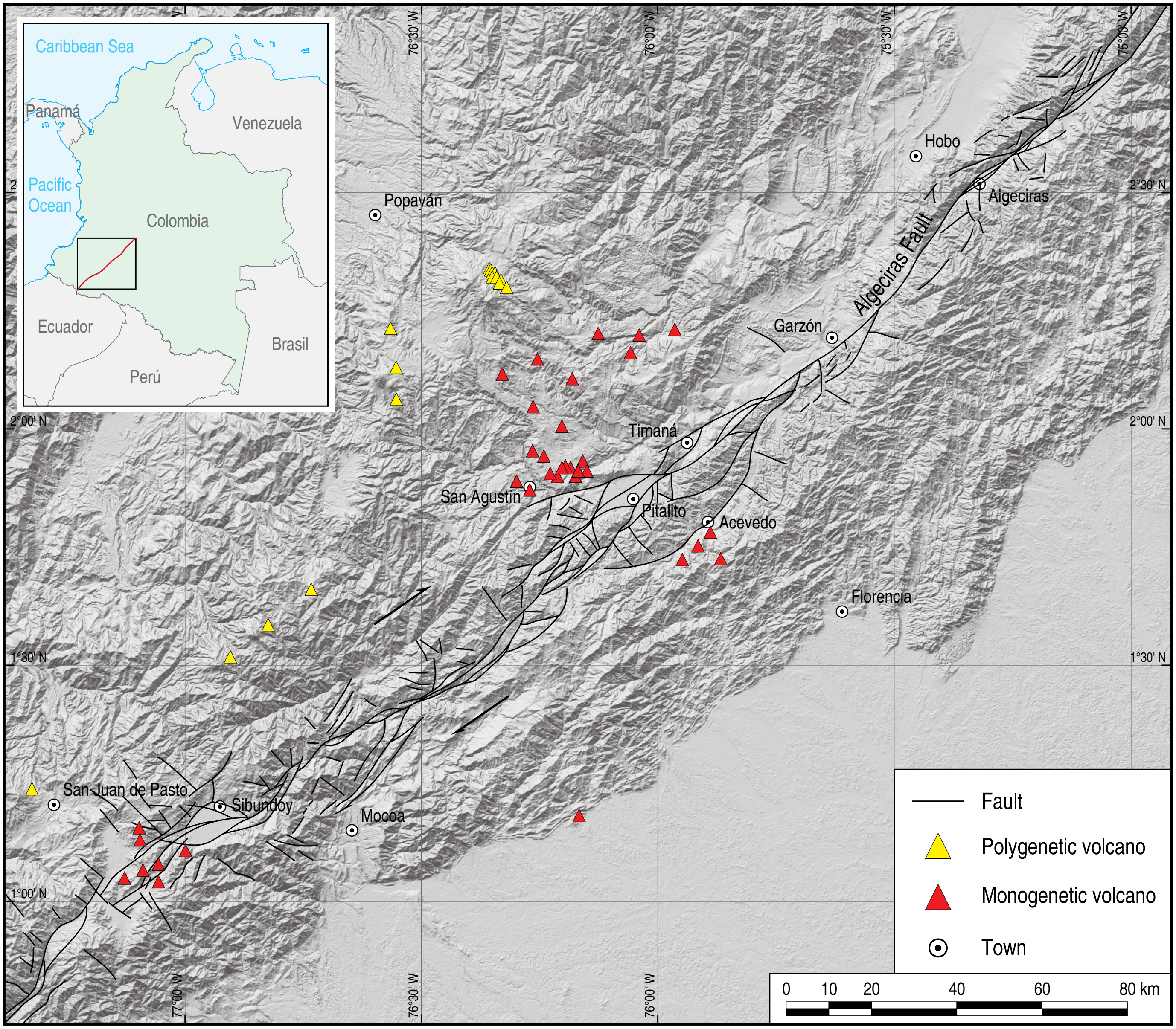

Figure 17. Shaded relief image with the mapping of the Algeciras Fault System (Modified from Velandia, et al. 2005 and Gómez et al., 2005). Notice that AMVF and Guamuez-Sibundoy group are associated to pull–apart basins.

The sample from the Tabor Volcano is basaltic in composition, with porphyritic texture containing phenocrystals (7.3%) mainly of clinopyroxene and orthopyroxene and some olivine. They are embedded in a matrix (84.9%) of fine–grained made up of microcrystals of plagioclase, clinopyroxene, and iron oxides; occasionally, pyroxene aggregates are observed.

The lavas of the Alsacia Volcano present porphyritic and holocrystalline texture, made up of phenocrystals of pyroxene and olivine, with crystalline aggregates of pyroxenes in a fine–granular matrix. Locally phenocrystals and microcrystals are oriented. The phenocrysts (12–20 %) are olivine with iddingsite alteration rim, clinopyroxene with resorbed core and rim, and some orthopyroxene, as well as aggregates (4.8 to 8.8 %) of these three minerals. The matrix (75–78 %) is made up of plagioclase, clinopyroxene, olivine, and iron oxides. In one of the analyzed samples, the presence of a quartzite xenolite and phlogopite was reported (Figure 21).

The lava samples from the Moscopán Monogenetic Field volcanoes are generally gray to reddish, and to a lesser extent black, such as those associated with La China Volcano. They

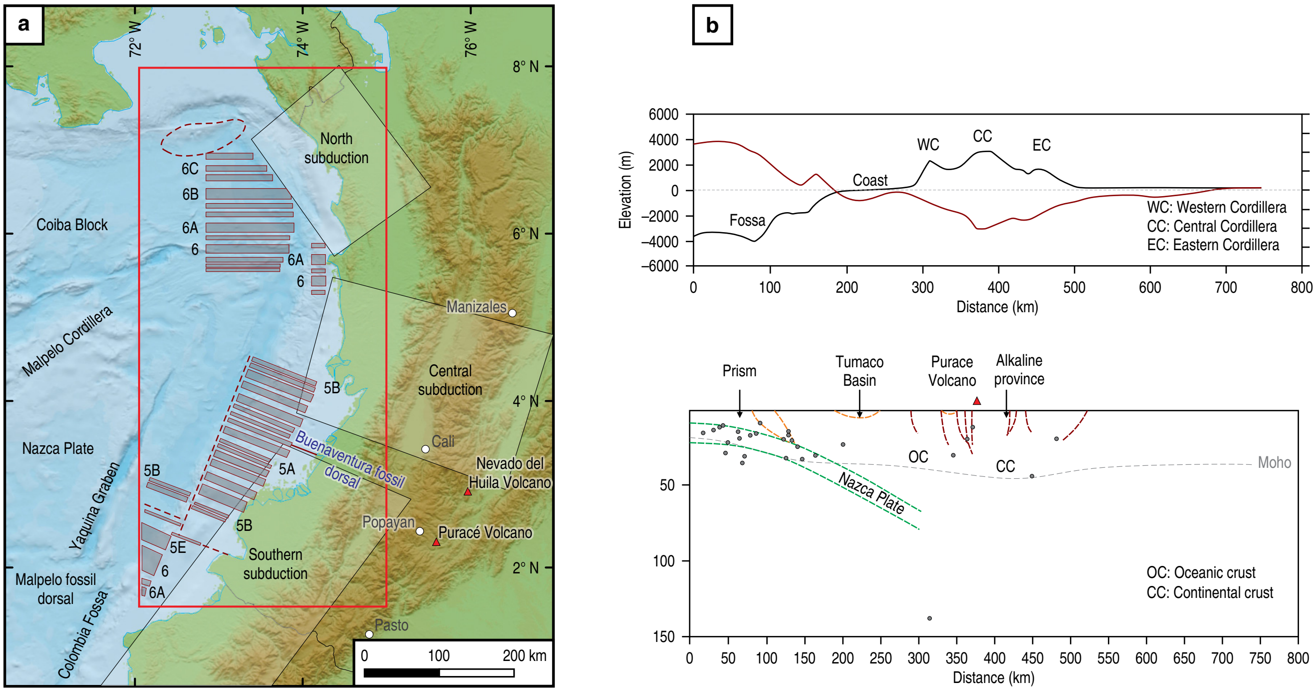

Figure 18. (a) Magnetic anomaly map ("chrons" 5A, 5B, 5E, 6, 6A, 6B, and 6C, ages 10 and 25 Ma) and location of the Buenaventura dorsal fossil (Modified from Hardy, 1991). Subduction segments after Arcila & Dimaté (2005). **(b)** Vertical sections perpendicular to the direction of the trench can characterize the geometry of Benioff plane and the depth of the associated seismicity (after Monsalve & Arcila, 2009).

present aphanitic, massive to slightly vesiculated and locally scoriaceous textures. In some cases, are medium porphyritic such as those of Merenberg and Santa Leticia. Kroonenberg et al. (1982a) reported quartz xenocrysts and quartz rich xenoliths surrounded by augitic–rich rim in the olivine basalts and andesites. Additionally, Cárdenas et al. (2002) reported, for some of the lavas of this region, vesicles occasionally filled with zeolites, calcium, magnesium, iron, and silica.

The andesitic lavas of the Merenberg and El Pensil Volcanoes, from the Moscopán Monogenetic Field, consist of sparse phenocrysts of olivine, clinopyroxene, and orthopyroxene included in a pilotaxic matrix of a tabular plagioclase, sporadic olivine, clinopyroxene, and opaque minerals (Kroonenberg et al., 1982a, 1987). These authors indicate the similarity with the olivine basalts, since they also present few phenocrysts of plagioclase. Velandia et al. (2001b) indicate a similar mineralogical association for La Palma volcano lavas, with few plagioclase sometimes zoned phenocrysts.

The lavas of the volcanoes of ISMVF are microporphyritic to glomeroporphytic rocks, with allotriomorphic and subidiomorphic texture. These lavas have serial distribution that includes olivine, pyroxene, plagioclase phenocrystals, and crystalline aggregates. The matrix is microcrystalline generally unequal to fluid and composed of plagioclase, augite, and occasionally glass unaltered (Cárdenas et al., 2002), for instance, see Trébol Volcano in Figure 22.

Kroonenberg et al. (1982a, 1987) petrographically described the rocks of this sector as basalts with abundant olivine phenocrysts with yellow iddingsitic rim and strongly zoned clinopyroxenes (titanoaugite), in a matrix composed of tabular plagioclase, abundant magnetite and some brown glass, partially recrystallized to dendritic olivine. However, Rodríguez (2017) and Rodríguez & Sánchez (2017) described a similar mineralogical association for samples of juvenile scoriaceous pyroclastic material from El Morro Volcano, from the MMVF.

The sample of the statue of the Pre–Columbian Augustinian culture, analyzed by Bergt (1899), is porphyritic with well–formed augite and olivine crystals with oxidation on the crystal margins; the two minerals have glass inclusions. The matrix is composed of augite, olivine, sparse feldspar, and brownish glass.

The lavas of the AMVF present microporphyitic, microlytic, hyalocrystalline, and amigdaloydal textures, with 22 to 40 % phenocrysts and 60 to 78 % matrix. The matrix is made up of clinopyroxene, olivine, opaque, and glass (Rodríguez et al., 2003).

Kroonenberg et al. (1982a, 1987) classified these lavas as ultrabasic rocks due to the absence of plagioclase in the matrix, occurring as an interstitial mineral among abundant augite, opaque minerals, biotite crystals, and less common secondary

→

Figure 19. Mapping of the cones and lava flows of the monogenetic volcanoes using a shaded relief image in the UMV. The numbers correspond to the volcanoes in Table 1. (MMVF) Moscopán Volcanic Field, (ISMVF) Isnos–San Agustín Volcanic Field, (AVCF) Acevedo Volcanic Field.

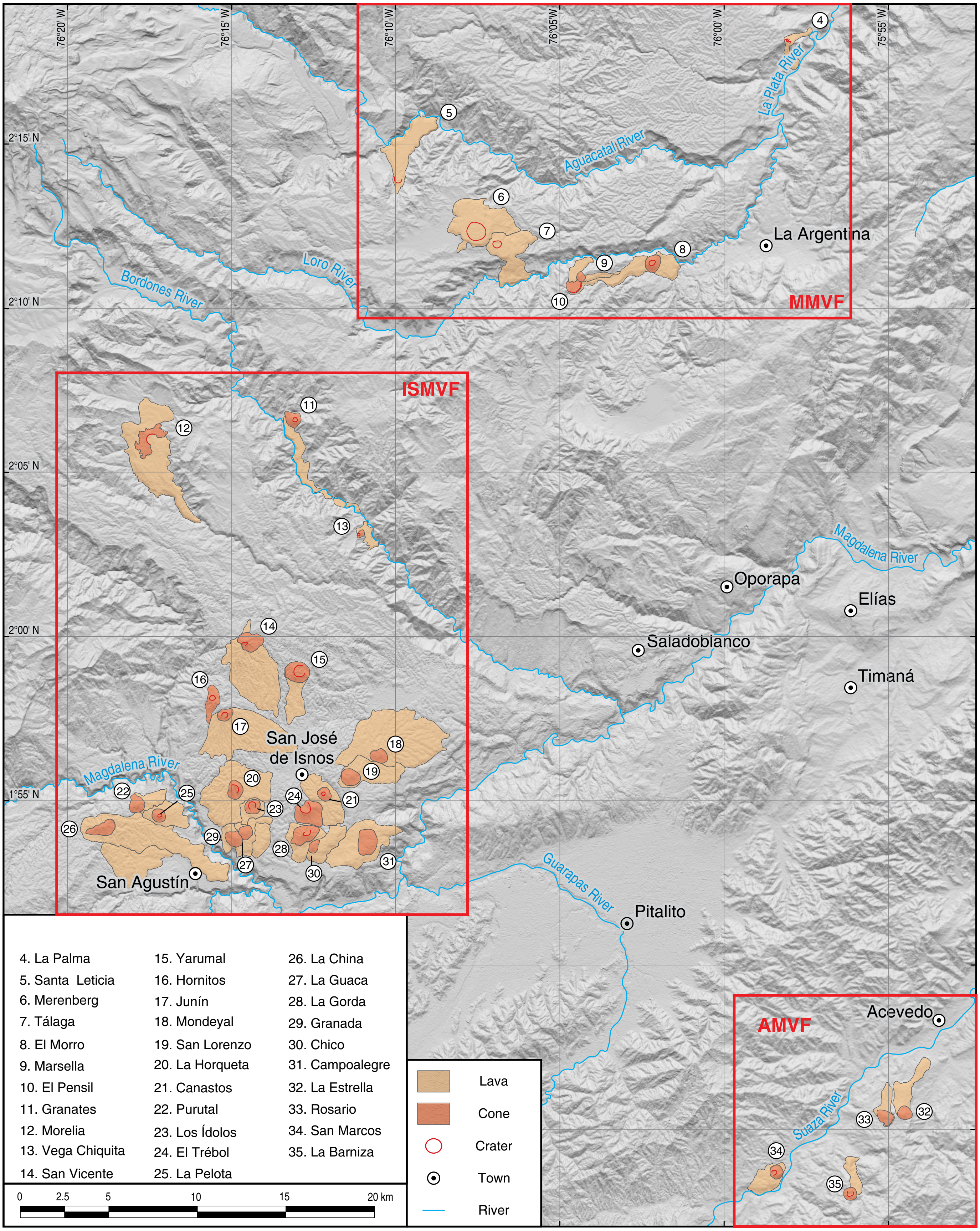
76°20' W
76°15' W
76°10' W
76°05' W
76°00' W
75°55' W
2°15' N
2°10' N
2°05' N
2°00' N
1°55' N
MMVF
ISMVF
AMVF
La Plata River
Aguacatal River
Loro River
Bordones River
Magdalena River
Guarapas River
Suaza River
La Argentina
Oporapa
Elías
Saladoblanco
Timaná
San José de Isnos
San Agustín
Pitalito
Acevedo
4. La Palma
5. Santa Leticia
6. Merenberg
7. Tálaga
8. El Morro
9. Marsella
10. El Pensil
11. Granates
12. Morelia
13. Vega Chiquita
14. San Vicente
15. Yarumal
16. Hornitos
17. Junín
18. Mondeyal
19. San Lorenzo
20. La Horqueta
21. Canastos
22. Purutal
23. Los Ídolos
24. El Trébol
25. La Pelota
26. La China
27. La Guaca
28. La Gorda
29. Granada
30. Chico
31. Campoalegre
32. La Estrella
33. Rosario
34. San Marcos
35. La Barniza
0 2.5 5 10 15 20 km
Lava
Cone
Crater
Town
River

Table 2. Morphometric parameters of small–volume UMV volcanoes.

Name	Cone height (Hco)	Cone basal diameter (Dco)	Crater diameter (Dcr)	Crater depth (Pcr)	Cone slope	Hco/Dco	Dcr/Dco	Morphological classification
Metaima Monogenetic Volcanic Field								
1. Tabor								
2. Guacharacos								Amorphous
3. La Alsacia								Ideal
Moscopán Monogenetic Volcanic Field								
4. La Palma								Ideal
5. Santa Leticia	25							
6. Merenberg	80							
7. Tálaga	71			31				
8. El Morro	106	921	332	29	42	0.115	0.360	Ideal
9. Marsella	62	532	190	13	43	0.117	0.357	Ideal
10. El Pensil	60	794	770	18	55	0.076	0.970	
Isnos–San Agustín Monogenetic Volcanic Field								
11. Granates	100	956	249	31	56	0.105	0.260	Ideal
12. Morelia								
13. Vega Chiquita		424	146	7	36	0.000	0.344	
14. San Vicente	109	1191	208	58	23	0.092	0.175	Gully
15. Yarumal	81	1269	655	22	18	0.064	0.516	Horseshoe
16. Hornitos	125	1112	293	34	13	0.112	0.263	Gully
17. Junín	71	811	312	43	27	0.088	0.385	Horseshoe
18. Mondeyal	71	900	40	23	20	0.079	0.044	Tilted
19. San Lorenzo	79	1010			38	0.078	0.000	Amorphous
20. La Horqueta	141	959	472	79	36	0.147	0.492	Horseshoe
21. Canastos	68	741	209	9	27	0.092	0.282	Ideal
22. Purutal	123	970			38	0.127	0.000	Amorphous
23. Los Ídolos	58	868	400	51	31	0.067	0.461	Horseshoe
24. El Trébol	114	1568	524	56	35	0.073	0.334	Horseshoe
25. La Pelota	104	776	192	18	35	0.134	0.247	Ideal
26. La China	134	1229	100		25	0.109	0.081	Amorphous
27. La Guaca	64	745			23	0.086	0.000	Amorphous
28. La Gorda	131	1362	329	84	18	0.096	0.242	Horseshoe
29. Granada	142	958			36	0.148	0.000	Amorphous
30. Chico	80	696	83	10	19	0.115	0.119	Ideal
31. Campoalegre	157	1241			28	0.127	0.000	Amorphous
Acevedo Monogenetic Volcanic Field								
32. La Estrella	126	794	72		48	0.159	0.091	Ideal
33. Rosario	54	848	179	49	22	0.064	0.211	Horseshoe
34. San Marcos	43	747	264	10	32	0.058	0.353	Gully
35. La Barniza		778	326	46	36	0.000	0.419	Amorphous

Table 3. Mineralogy and classification of the samples of the San Agustín–Isnos Volcanoes.

	Sample number					
	IGM–163323	**IGM–163324**	**IGM–163325**	**IGM–163326**	**IGM–163327**	**IGM–163328**
Mineralogy (%)						
Phenocrysts	27.9	23.9	28.6	26.5	29.3	29.2
Clinopyroxen (pigeonite)	13.3	15.9	20.,6	13.9	16.6	16.6
Orthopyroxene	1.3	–	–	–	–	–
Olivine	13.3	8.0	8.0	12.6	13.3	12.6
Matrix	60.6	59.2	67.9	66.6	62.5	65.2
Plagioclase (labradorite)	52.0	44.6	57.3	56.0	50.6	55.3
Clinopyroxene	6.6	5.3	4.0	2.6	2.6	3.3
Magnetite (?)	1.0	7.9	4.4	5.0	6.4	5.4
Vesicles	4.6	16.6	0.6	6.6	6.6	1.3
Accesories						
Opaque	0.6	–	–	–	–	–
Glass	–	–	–	–	0.6	–
Calcite in amygdules	–	–	–	–	–	Tr
Classification			Basalts with olivine and pyroxene			
Tr: trace minerals.						

Source: Núñez et al. (2001)

carbonates. They also report a sample of this type in San José de Isnos, which consists of olivine phenocrystals and augite microcrystals in a brown vitreous matrix, without plagioclase. For this sector Rodríguez & González (2004) report the presence of corroded olivines in desequilibrium with the matrix and sometimes altered to serpentine along the fractures or rims, and Kroonenberg et al. (1982a) reported spinel wherlite and garnet–bearing lherzolitic cumulates.

The volcanoes of the grupo Guamuez–Sibundoy have been little studied. Küch (1892) petrographically analyzed two basalt samples, one of them from "Cerro Campanero in the Cocha in Pasto" as well as other samples around the Cocha and in Sibundoy (headwaters of the Putumayo River) collected in the Espinoyaco, Pedroyaco, and Jacuco Rivers from the area. One of them classifies in the basalt–pyroxene basaltic andesite boundary due to the high content of olivine and because it has augite in the matrix; the others are located in the field of pyroxene andesites with amphibole and some with sporadic biotite coming from the road to Cerro Patascoy de Santa Lucía.

In particular, the sample from the Cerro Campanero is described by Küch (1892) as black, somewhat dense and vesiculated, with very abundant phenocrysts of olivine and augite on a matrix consisting of feldspars, augite, and colorless glass. Sibundoy's lavas present porphyritic to microporphytic texture, abundant vesicles filled with zeolites. The phenocrystals are of plagioclase, clinopyroxene, with a glomeroporphyritic texture and some crystalline olivine agglomerates. The matrix is made up of oriented plagioclase microliths, less common opaque minerals and a ferruginous material possibly glass in the process of devitrification (Núñez, 2003; Rodríguez & González, 2004).

8. Geochemistry of the Monogenetic Volcanic Field

The results of the chemical analysis of whole rock major and trace element available in previous works. Küch (1892), besides the petrographic analysis of the sample from Cerro Campanero, reports a silica content of 46.45%, but does not present the chemical analysis table. Velandia et al. (2001b) reports for the lavas of La Palma Volcano 51.73% and 52.30% of SiO_2 and 3.82% and 4.07% of Na_2O, indicating they are basalts and basaltic andesites of calc-alkaline signature.

The silica content of the rocks of the basaltic fields presented in this work, varies between 40 and 59 wt % and the alkalis range from 2.57 to 6.75 wt %, so that the samples plot in the picrobasalt, tephrite, basanite, trachybasalt, trachyandesite, basalt, basaltic andesite, and andesites fields on a total alkali versus silica diagram (Le Maître, 1989) (Figure 23).

Considering that some samples do not present LOI data, the available data are plotted in the discrimination diagram SiO_2 vs. Nb/Y (Figure 24). Those corresponding to MeMVF plot in the field of basaltic and calcoalkaline basaltic andesites. The composition of the sample of Isnos (UMV) plot in the field of trachyandesite, as do the samples from the MMVF, whereas

Table 4. Mineralogy and classification of the samples of the Guacharacos, Tabor, and Alsacia Volcanoes.

Sample number		VG–002	VG–003	VG–004	VG–005	VG–006	CG–010	VG–011	VG–012	JGT–1586	JGT–2399	JGT–654
Volcano		Guacharacos								Tabor	Alsacia	
Coordinates	Latitude N	4° 24’ 20.970”	4° 24’ 23.624”	4° 24’ 23.262”	4° 24’ 46.870”	4° 24’ 23.682”	4° 24’ 52.523”	4° 24’ 42.375”	3° 30’ 26.702”	4° 23’ 55.318”	4° 25’ 58.12”	4° 25’ 59.509”
	Longitude W	75° 11’ 33.284”	75° 11’ 43.179”	75° 11’ 46.194”	75° 12’ 0.789”	75° 11’ 26.543”	75° 11’ 24.251”	75° 11’ 19.761”	75° 11’ 14.333”	75° 10’ 37.305”	75° 25’ 15.56”	75° 25´ 30.788”
Mineralogy (%)												
Phenocrysts		25	30	30	40	20	20	20	20	16	20	25
Clinopiroxeno		14	14	14	18.2	10.5		10.5	10.5	5	2	8
Orthopyroxene		6	6	6	7.8	4.5		4.5	4.5	2	1	
Olivine		4	9	8	9.2	4.6	20	4.6	4.6	1	10	12
Plagioclase		0.5	1	1.7	4.8	0.4	–	0.4	0.4	Tr		
Pyroxene aggregates										8	6	5
Xenolite		0.5	–	–	–	–	–	–	–			
Fe oxides		–	–	0.3	–	–	–	–	–		1	
Matrix		75	70	70	60	80	80	80	80	84	80	75
Glass		22.5	18.2	21	12	24	24	24	24	Plagioclase	Plagioclase	Plagioclase
Microlites		52.5	51.8	49	48	56	56	56	56	Fe–Ti oxides	Clinopyroxene	Fe–Ti oxides
Plagioclase		39.4	38.8	36.7	36	42	42	42	42	± Clinopyroxene	Olivine	Clinopyroxene
Pyroxene		10.5	10.4	9.8	9.6	11.2	11.2	11.2	11.2		Fe–Ti oxides	
Opaque		2.6	2.6	2.5	2.4	2.8	2.8	2.8	2.8			
Classification		**Basalts with pyroxene and olivine**										

Tr: trace minerals.

Source: Guacharacos from Galindo (2012) and Tabor–Alsacia data from this chapter.

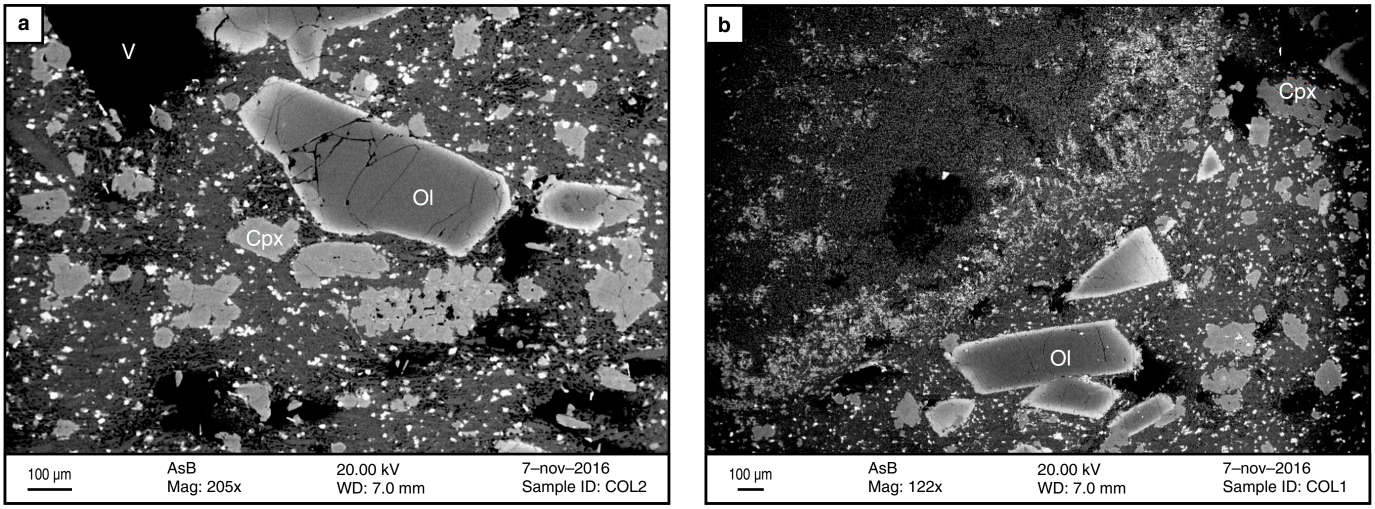

Figure 20. SEM images for Guacharacos samples. **(a)** General appearance with presence of olivine (Ol) phenocrysts, clinopyroxene (Cpx), and irregular vesicles (V). **(b)** Detail of an inclusion, contrast between the basalt in the lower right corner and the inclusion in the upper left corner with dissolution textures (vesicle in the center). The inclusion presents two gray tons that are interpreted as two phases of alteration. The zoning of the olivines is more pronounced since the contrast of the image was modified to observe the inclusion in detail (Cortés, 2017).

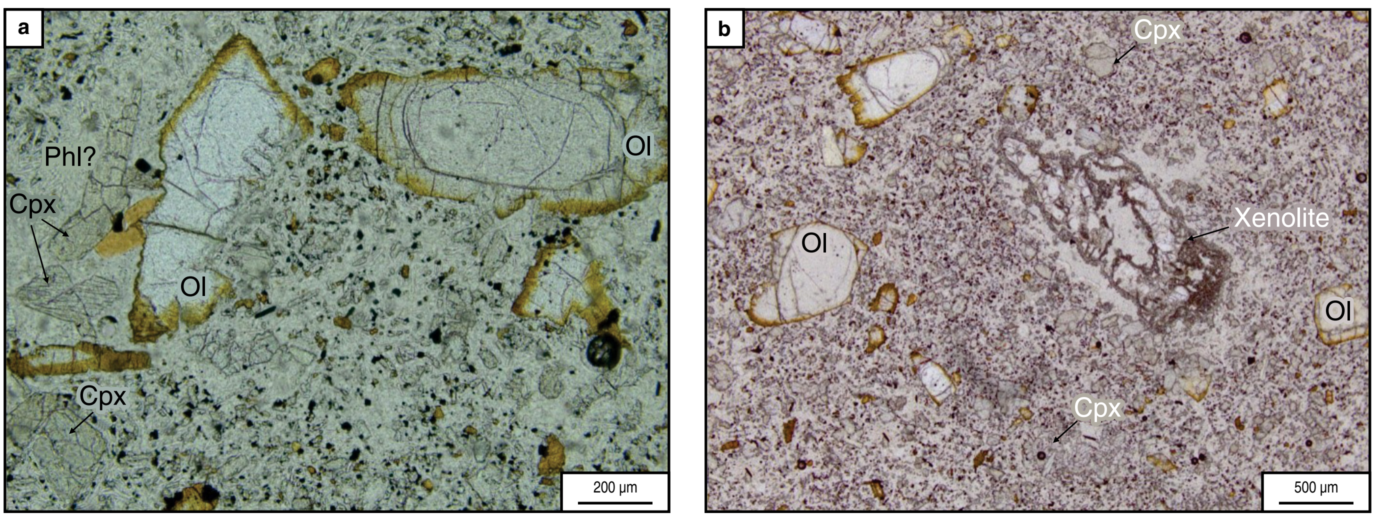

Figure 21. Photomicrographs of the JGT–88 sample. **(a)** 10X objective and parallel nicols. Olivine with resorbed rim and phlogopite. **(b)** 4X objective and parallel nicols. Rock texture and quartzite xenolite. (Ol) Olivine, (Cpx) Clinopyroxene, (Phl) phlogopite.

those of El Morro, from the same area, plot in the field of alkaline basalts.

All samples from the AVP display high values of Ni (110 to 370 ppm) and Cr (420–710 ppm) and have Mg# ratios ranging 55–72, except those of Merenberg–El Pensil (from MMVF) which values vary between 40 and 80 ppm for Ni, 125 to 280 ppm for Cr, and Mg# = 44–49.

The basalts have Nb concentrations greater than 20 ppm corresponding to high–Nb basalts. Those rocks have spatial proximity and temporal association with the CVCh, which more recent lavas have adakite signature (Monsalve et al., 2015) as well as positive to negligible Eu anomalie, low Y and Yb concentrations, and high Sr/Y and La/Yb ratios (Defant & Drummond, 1990).

The MeMVF in the Ibagué–Cajamarca region comprises volcanoes with basalts and basaltic andesites and they have close spatial proximity and temporal association with Cerro Machín Volcano, which also have an adakite signature (Laeger et al., 2013; Regnier, 2015). The geochemical characteristics of the MMVF samples include: SiO2 (52–54 wt %) at high MgO (10–12 wt %), and Mg# ratios vary 63–69. They also have high total alkalis (4–5 wt %) and the Sr/Y range 30–36, typical of normal arc (those values are the lowest of all the sampled groups), however the La/Yb = 18 is probably due to enrichment in La, not to depletion in Yb.

Samples from the Guacharacos and Tabor Volcanoes correspond to high magnesium andesites. The occurrence of these

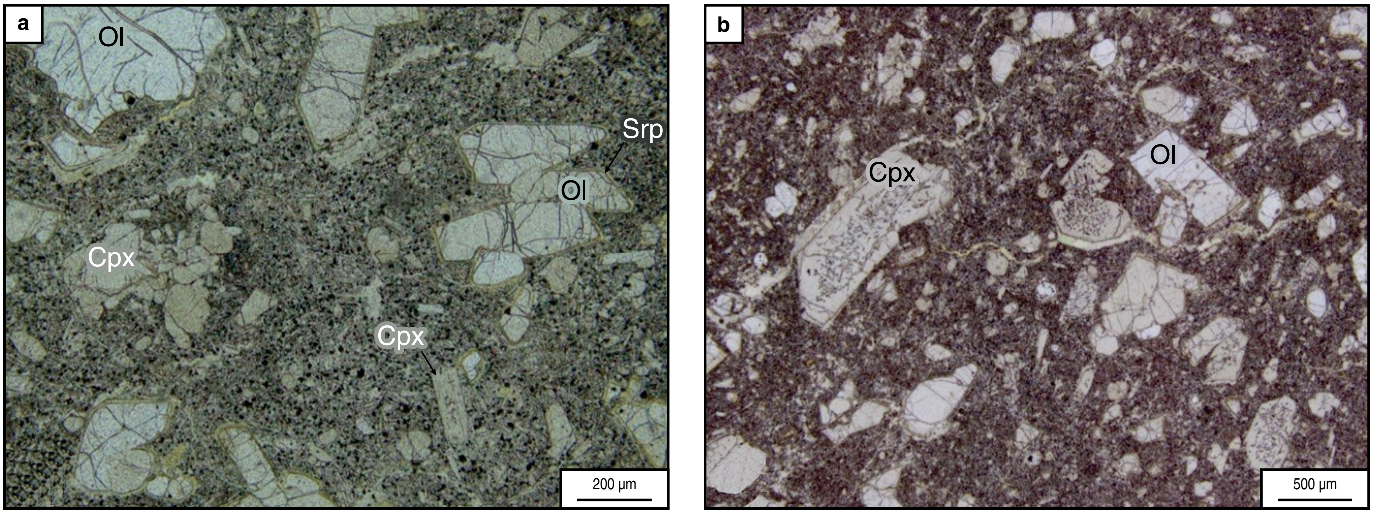

Figure 22. Photomicrographs of IGM–163512 sample from El Trébol Volcano. **(a)** 10X objective and parallel nicols. Rock texture and mineral aggregates, olivinen (Ol) with serpentine (Srp) edges. **(b)** 4X objective and parallel nicols. Clinopyroxenes (Cpx) with corroded interiors and calcite veins.

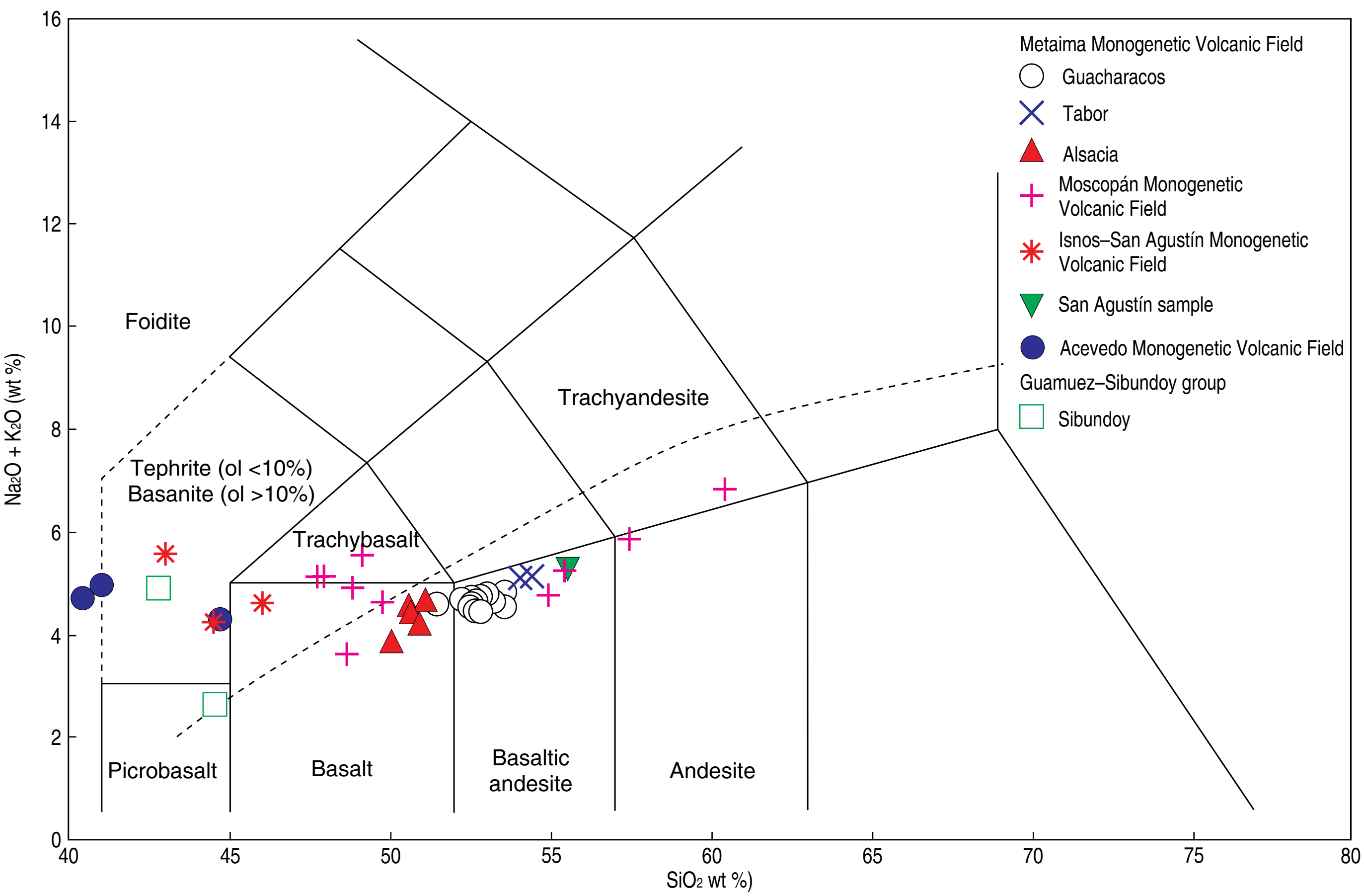

Figure 23. TAS classification diagram for Colombia rear–arc samples. The dash line that separates alkaline from subalkaline fields is from Irvine & Baragar (1971). Guacharacos–Tabor–Alsacia are samples from Ibagué–Cajamarca region. Data from Kroonenberg et al. (1987), Núñez et al. (2001), Rodríguez & González (2004), Galindo (2012), Regnier (2015), Rodríguez (2017), and this chapter.

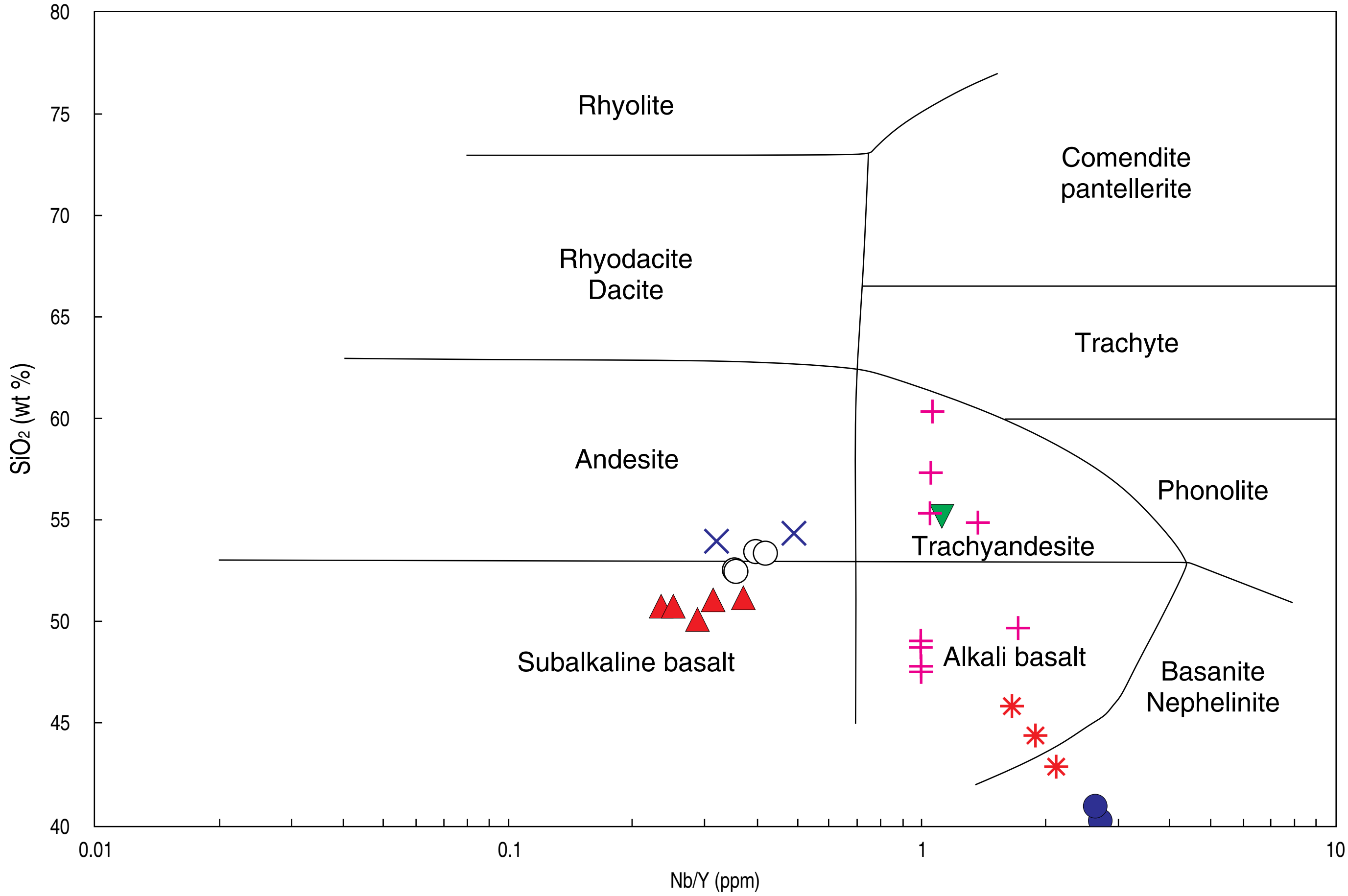

Figure 24. SiO_2 vs. NB/Y showing the fields for the samples. The key is the same as in the Figure 23. Notice the group of El Morro (from MMVF), plotting in alkali basaltic field, and one sample from San Agustin (from ISMVF), plotting in the trachyandesite field. Legend as in Figure 23.

rocks in volcanic arcs implies that they are generated in, or equilibrated with, mantle peridotite (i.e. Wood & Turner, 2009), so they represent primary magmas. There are several models to explain the origin of these magmas, which can be the partial fusion of the lithospheric mantle or material of asthenospheric origin, being the most common parent material peridotite and eclogite (e.g., Bryant et al., 2010; Calmus et al., 2003; Hoang et al., 2009; Kelemen et al., 2014; Negrete–Aranda & Cañón–Tapia 2008; Pallares et al., 2007). For Regnier (2015), those magmas are not related with those associated to Cerro Machín Volcano. To Wang et al. (2020) the association adakite and high magnesium andesites could represent a mechanism of interaction between slab melts and mantle in subduction zones.

In Harker–diagrams (Figure 25), major components of all samples including SiO_2, Al_2O_3, K_2O, and Na_2O show decreases with increasing MgO. The olivine basalts of Acevedo area and Guamuez–Sibundoy region also show decreases in TiO_2 with increasing MgO, while the samples from Isnos and Ibagué–Cajamarca regions show a slight positive correlation. Samples of all regions show a clear positive correlation between CaO and MgO and FeO*. Both the basalts and andesites of Ibagué–Cajamarca area have higher MgO content that andesites of Moscopán Monogenetic Volcanic Field.

The rare earth element (REE) patterns (Figure 26) define two groups: The alkalibasaltic to nephelinitic lavas (from Acevedo and Isnos–San agustín), that are more enriched in light REE than the other groups and the alkalibasalts of El Morro, the subalkaline andesites samples of Moscopán, and the calcoalkaline basalts and high magnesium andesites of the Metaima Field. The sample of San Agustín (Isnos–San Agustín is also included into this group). There are no data available for Guamuez–Sibundoy samples. All the groups have a similar pattern of in heavy REE, being the subalkaline andesite suite of Moscopán slightly more enriched.

Kroonenberg et al. (1987) differenced two rock series for the "Alkalic Volcanic Province", on the primitive mantle–normalized data. Here, the curve of the available data from the alkali basalt of El Morro is used as a reference to separate the two series (Figure 27a, 27b), although the alkaline character of the sample, the primitive mantle–normalized trace element pattern of this rock show more affinity with the subalkaline suite.

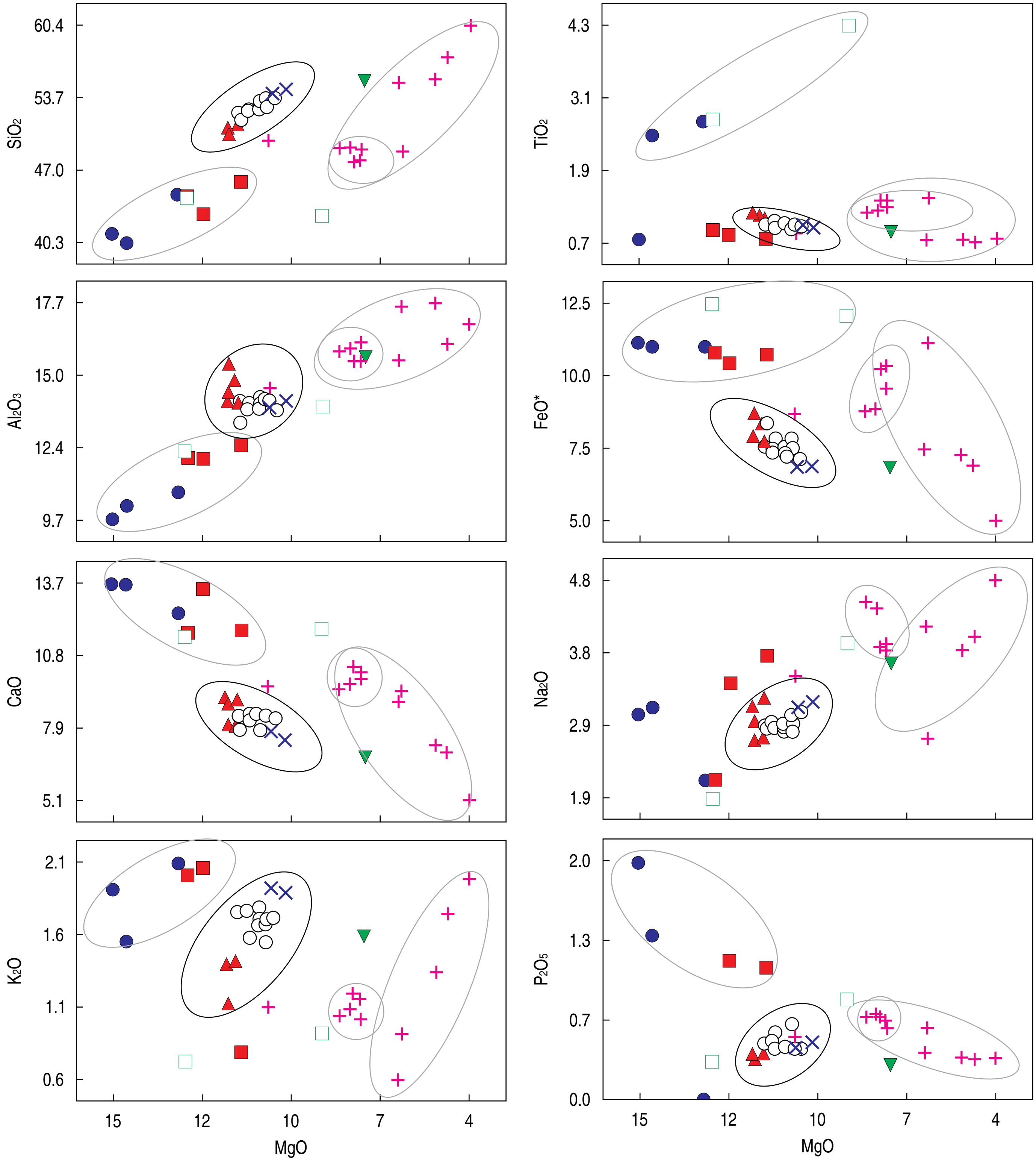

Figure 25. MgO (wt %) vs. major elements (wt %) for basalts and basaltic andesites. Samples grouped by geografical localities. Some chemical characteristic are similar for Acevedo, Isnos, and Guamuez–Sibundoy samples. El Morro samples defines a subgroup of La Argentina región (MMVF). San Agustín sample generally lies in the MMVF. Legend as in Figure 23.

The primitive mantle–normalized trace element patterns for the alkalibasaltic to nephelinitic lavas (Figure 27a) show incompatible elements enrichment and depletion in HREE; the enrichment in LREE could be the result of low degrees of partial melting of a garnet bearing source. Kroonenberg et al. (1987) pointed out that the parent alkalibasaltic magma originated by partial melting

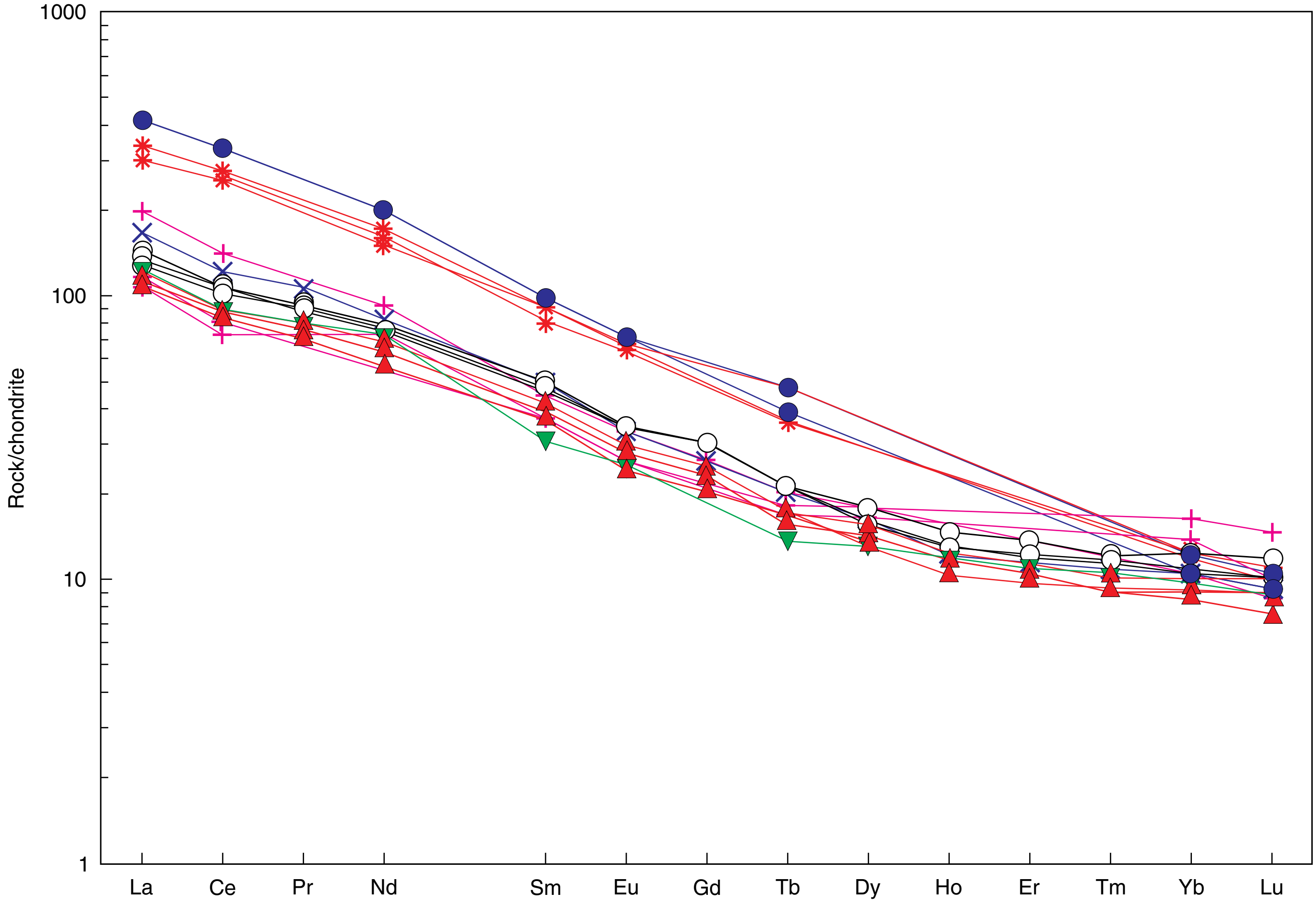

Figure 26. Chondrite–normalized rare earth element patterns for primitive basalts and andesites. Legend as in Figure 23.

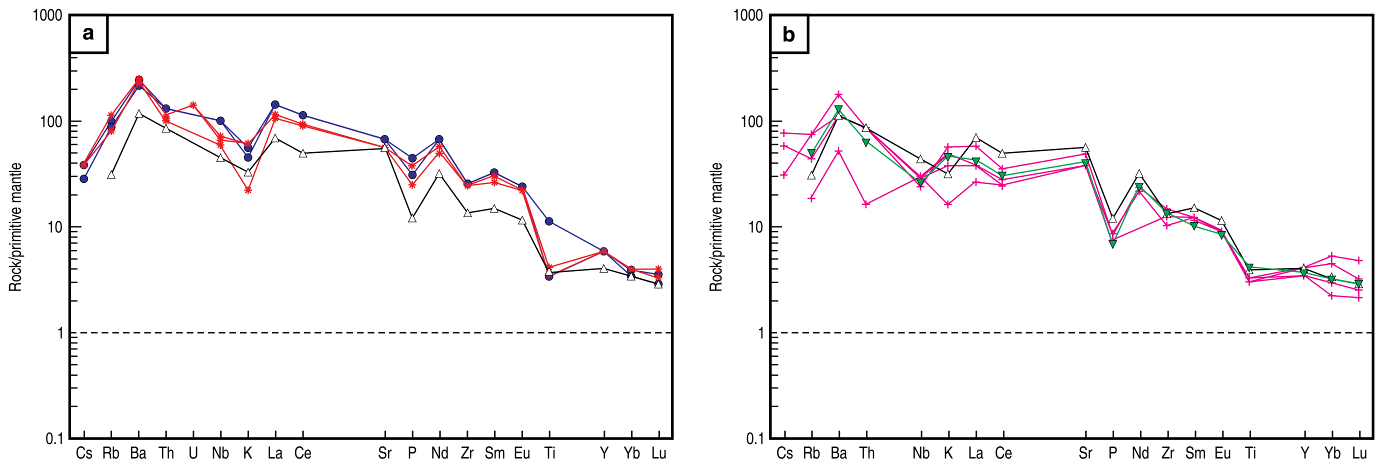

Figure 27. Trace elements normalized to primitive mantle following Sun & McDonough (1989). **(a)** Alkalibasaltic to nephelinitic lavas from Acevedo and Isnos–San agustín and El Morro Volcanoes (black tringles). **(b)** Samples of MMVF including subalcaline serie from Merenberg–El Pensil Volcanoes and alkalibasalt from El Morro Volcano. Sample from ISMVF have similar patron to MMVF samples. The curve of El Morro sample (here in black) is used as reference in both diagrams. Legend as in Figure 23.

of garnet lherzolite within the upper mantle. The garnet bearing source is also suggested by the high La/Yb ratios (>50 for the Acevedo's nephelinites and 36–40 for the Isnos' alkali basalts) and the low HREE contents. However, the high values of Ba/La (>15 and >22, respectively) may indicate a role of the subducting slab fluids mainly for Isnos–San Agustín volcanoes.

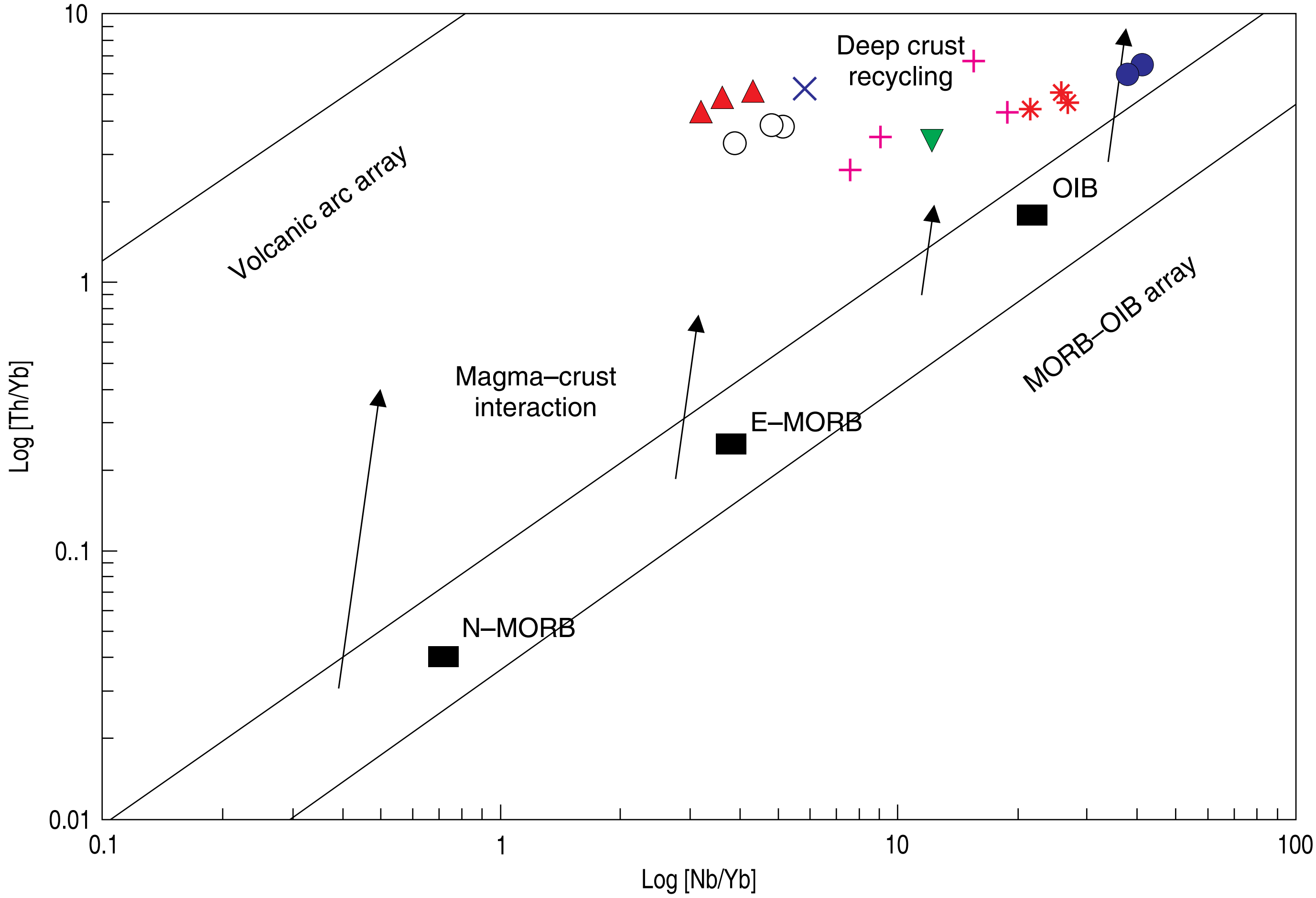

Figure 28. Th/Yb–Nb/Yb projection (after Pearce, 2008) showing the effect of crustal contamination or crustal recycling by subduction for the samples of monogenetic volcanic fields. Legend as in Figure 23.

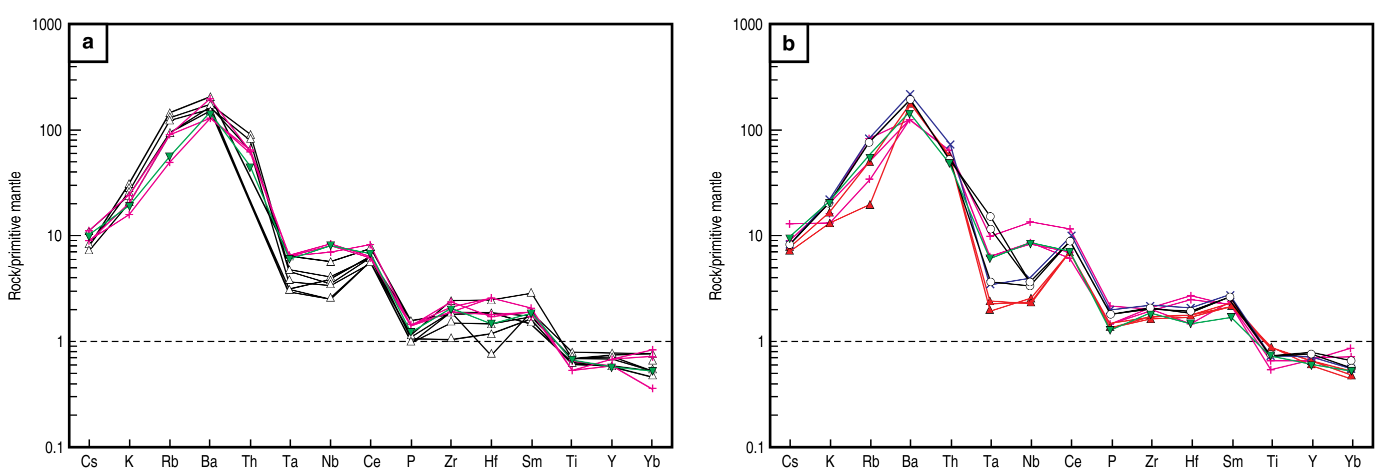

Figure 29. N–MORB–normalized trace element abundance spider diagram (Sun & McDonough, 1989), for subalkaline suite from MMVF and sample from San Agustin (ISMVF). **(a)** Compared with calcalkaline andesites from CVCh in the front arc (black trinagles). **(b)** Compared with calcalkaline basalts and basaltic andesites from MeMVF.

Mantle normalized pattern of the subalkaline rocks show lower LREE and similar HREE patterns to the alkaline suite (Figure 27b), reflecting a greater degree of partial melting in comparison with the former group. The higher Ba/La (>20) and Ba/Nb (> 30) ratios suggest interaction with subducting slab fluids.

Pearce (2008) gives examples of continental margin volcanic rocks and oceanic plateaus erupted through continental lithosphere that may be contrasted with true oceanic basalts by their trends to high Th/Yb (upper crustal interaction and interaction with mantle lithosphere containing an inherited subduction component). The samples plotted on the Th/Yb–Nb/Yb diagrame (Figure 28) shows the effects of subduction in displacing the volcanic basalts from the MORB–OIB array, indicating that Th–Nb variations that could reflect either direct crustal contamination or crustal recycling by subduction.

Sub–alkaline series from Moscopán samples is compared with Coconucos Volcanic Chain and Metaima samples on N–MORB–normalized trace element abundance spider diagram (Figure 29a, 29b). The patterns on both cases are similar showing Large Ion Lithophile Elements (LILE) elements enrichments (e.g., Ba, K, and Sr) and HFSE depletion (e.g. Nb–Ta and Ti). The subalkaline andesites of Moscopán are slightly less depleted on Nb and Ta than the other region and lack the anomaly of Nb–Ta, typical of subduction related magmatism, which is present in the calcoalkaline samples of Coconucos Volcanic Chain and in higher extent in calc–alkaline basalts and basaltic andesites of Metaima Monogenetic Field. Additionally, some representative trace elements abundances for all these samples include high Sr (>600 ppm), Th (5.5-8.6 ppm), and U (1.98–8.91 ppm) values. Finally, basalts from the Alsacia Volcano are slightly more depleted in some HFSE elements than the andesites (Figure 29b).

9. Discussion

With the existing information on small–volume basaltic volcanoes in Colombia, which are in a rear–arc position behind the active volcanic front arc, and although the definition of volcanic field is under debate (i.e., Cañón–Tapia, 2016), it is proposed the existence of at least four monogenetic volcanic fields, taking into account factors such as: Geographical distribution, structural relationships, composition, and possible tectonic control, among others (i.e., Connor & Conway, 2000; Gencalioglu–Kuscu & Geneli, 2010; Kereszturi, G. & Németh, 2012; Le Corvec et al., 2013; van den Hove et al, 2017).

The volcanoes of the Ibagué–Cajamarca region —where the MeMVF is found— and the UMV —where the Moscopán, Isnos–San Agustín, and Acevedo Monogenetic Volcanic Fields are defined— are better studied than the group of volcanoes in the Guamuez–Sibundoy region. The later were identified through photogeological studies (Ceballos et al., 1994; Flórez, 2003; Robertson et al., 2002) and correspond to small–volume volcanoes located at the E of Galeras Volcano, without defining a field volcanic due to lack of more data. The indications of its existence are given by its geographical position with respect to the active volcanic front, the reports on the basaltic composition of the Sibundoy and Cerro Campanero Volcanoes, as well as its morphology.

As indicated by Stein & Sella (2002 in Cañón–Tapia, 2016), it has been observed that most of the volcanic fields are in, or very close to, diffuse deformation zones or plate boundaries. The local environment of volcanic fields can be extensional, transient, or compressional and its regional distribution seems to be controlled by the regional structure of the lower crust and the upper mantle (Le Corvec et al., 2013; Torres et al., 2020; Ureta et al., 2020).

The presence of alkaline and sub–alkaline monogenetic basaltic volcanism in a "retroarc" position with respect to the chain of active volcanoes in Colombia is surely due to the complex tectonic configuration of the ANVZ in the NW corner of South America. Although this work does not attempt to reach a conclusion about the origin of these monogenetic fields, since the available data are not sufficient, attention is drawn to petrological and tectonic characteristics, discussing some observations from previous works.

In the UMV, Kroonenberg et al. (1982a) defined the Alkalibasaltic Volcanic Province and postulated, for volcanoes in the Santa Leticia–La Argentina area and the formerly called "Acevedo lava", corresponding in this work as Moscopán and Acevedo Monogenetic Fields, a sub–parallel alignment to Coconucos Volcanic Chain. However, considering the geochemical differences found between AMVF (ultrabasic) and MMVF (predominantly subalkaline), as well as the structural arrangement and composition (alkaline) of the volcanoes of the so–called ISMVF, the authors highlight the difficulty of explaining the basaltic volcanism of mantle origin with the sub–alkaline one related to subduction.

Schmitt–Riegraf (1983, 1989) and Kroonenberg et al. (1987) concluded that the alkaline and sub–alkaline series of Alkalic Volcanic and Alkalibasaltic Volcanic provinces are not related to each other, since the former would be primary magmas generated in a garnet lherzolite source in the upper mantle, while they consider that the andesitic basalts and andesites are similar to the calc–alkaline volcanism of SW Colombia. With regard to this appreciation, there are several factors that suggest, as initially raised by Kroonenberg et al. (1982a, 1982b), that the volcanism of the MMVF is "intermediate" between alkaline and that related to subduction, reflected in the composition of the products of the Merenberg and El Pensil Volcanoes, with geochemical characteristics related to subduction, which have differences and similarities with the Coconucos Volcanic Chain.

The differences between the volcanoes of the MMVF, with respect to this chain, include the monogenetic character, the geographical position (rear–arc and subparallel to it), the mineralogy (i.e., few phenocrysts of plagioclase), and the geochemistry (lower content in TiO_2 and Al_2O_3 and higher content in MgO, Na_2O, and P_2O_5) (Figure 30). On the other hand, some recent lavas from the CVCh show an adakitic signature (Monsalve et al., 2015) and it is noticeable that some samples from MMVF also fall within this field (Figure 31).

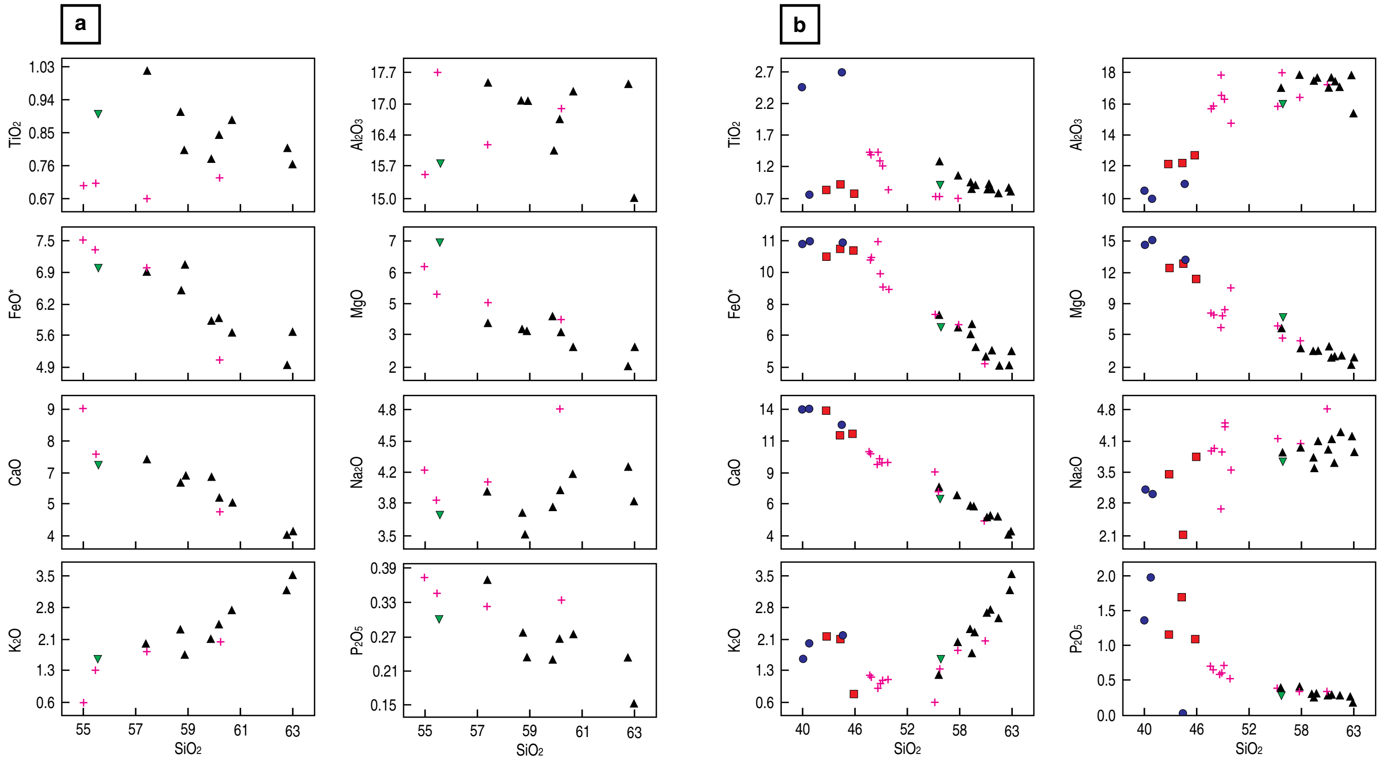

Figure 30. (a) Harker diagram for the volcanoes that make up the Alkalic Volcanic Alkalibasaltic Volcanic Province (Kroonenberg et al., 1982a, 1987). **(b)** The same data, compared with samples from the CVCh, where the subalkaline affinity rocks from MMVF and selected data from the CVCh are plotted. Also, for comparison, in Figure 26b, all the data including the alkaline samples from ISMVF and AMVF are plotted. Legend as in Figure 23. Black triangles are CVCh samples.

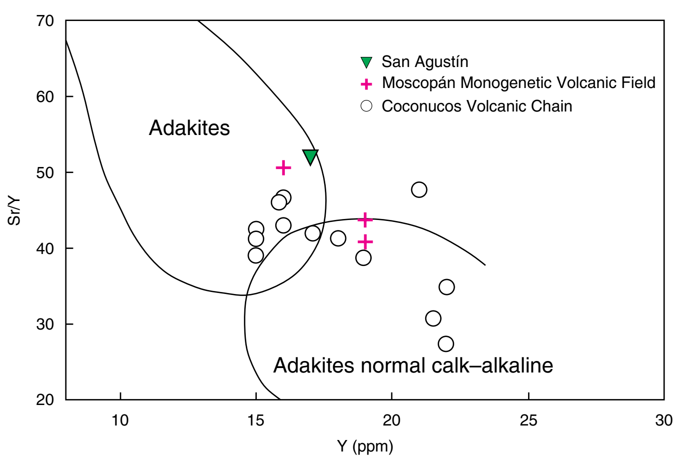

Figure 31. Adakite Discrimination Diagram (Defant & Drummond, 1990), comparing samples from the CVCh, the MMVF and the calkalcaline sample of San Agustín.

Particularly, for monogenetic fields defined in the UMV, the question arises as to whether two or more groups of adjacent volcanoes are part of a large field or can be considered independent, taking into account that groups of volcanoes in large volcanic fields can be separated by regions devoid of volcanic activity (i.e., Cañón–Tapia, 2016; Kereszturi et al., 2013).

The Isnos–San Agustín and Moscopán Volcanic Fields are built on thick ignimbritic deposits, dated 7.1 ± 0.3 Ma (Kroonenberg et al., 1981; 1982a), while for the "Acevedo basalts" an age of 31.2 ± 2.7 Ma is reported by Kroonenberg et al.(1982a), which indicates the existence of at least 2 fields in UMV. The authors' observation suggesting that the latest dating should be reviewed, should be considered. The finding, in this work, of volcanic edifices in Acevedo, some of them with well–preserved morphology (Figure 12), comparable with that of the volcanoes that are considered more recent in Moscopán and Isnos–San Agustín Volcanic Fields (Figures 6, 8, 9, and 10), suggests that volcanism in these two sectors is coeval.

On the other hand, some geochemical characteristics of the Acevedo and Isnos–San Agustin subgroups are similar (Figures 23–28), and may be genetically related to each other, the variation in composition being due to different degrees of fusion.

The Isnos–San Agustín and Moscopán Volcanic Fields are geographically closer, however, the existing geochemical data show that the ISMVF volcanoes are predominantly alkaline and those of Argentina sub–alkaline tholeitic, although in the former a sample of the area of San Agustín is reported as subalkaline and El Morro Volcano, in Argentina, has alkaline affinity, representing a mantle–derived magma composition that is transitional between subduction arc magmatism and rear–arc intraplate magmatism (Figure 26). This type of magmatism has been recorded in other parts of the world (i.e., Gencalioglu–Kuscu & Geneli, 2010; Maury et al., 2004).

It could be thought, preliminarily for El Morro Volcano, that the SW–NE structural control (Plata Fault), similar to the structural control in the ISMVF, could explain a composition of derived mantle magma, which is transitional between arc and intraplate magmatism.

The occurrence of alkaline and nephelinite basalt rocks east of the main volcanic chain of Colombia was considered by Kroonenberg et al. (1987), referring to the UMV, as a highly anomalous volcanic province.

Some tectonic considerations have been taken into account to propose the origin of volcanism in southern Colombia:

Kroonenberg et al. (1982a, 1987), postulated that the Alkalibasaltic Volcanic Province is located at the top of the expansion center that would correspond to the prolongation, towards the E, of the Malpelo Rift, allowing to explain the primitive nature of the magma; however, they pointed out about the need to review the age of the Acevedo basalts to confirm the relationship between volcanism and the development of the Panamá Basin.

Borrero & Castillo (2006) stated that the Carnegie Ridge collision, which they consider coupled to the Malpelo Rift, gave rise to a slab window that allowed the asthenospheric magma to rise and the formation of retro–arc volcanism in southern Colombia, including the Guamuez–Sibundoy region and the Alkalibasaltic Volcanic Province, considering that the source of the magmatism is the Galápagos Plume.

Monsalve & Arcila (2009) related the adakitic signature of the Puracé and Huila Volcanoes and the volcanism of the Alkalibasaltic Volcanic Province to a tectonic context given by the the Buenaventura fossil rift; they propose that the partial melting of metasomatized mantle associated with adakitic magma was responsible for generation of the high–Nb basalt of the Alkalibasaltic Volcanic Province

The characteristics described above could be related to the origin and composition of volcanism in this region, but there are other tectonic factors that have not been considered to establish the origin of the alkaline volcanoes, such as the structural position that corresponds to a distensive regime associated with pull–apart basins. These alkaline volcanoes are located mainly along transtensional faults, in pull apart basins, possibly caused by the displacement of the North Andean Block towards the NNE, due to the push of the Carnegie Ridge, moving along the zone of fault of the Andean eastern front, which would allow the rise of the magma.

Finally, the Alkalibasaltic Volcanic Province are in an area of high concentration of horizontal deformation (Arcila & Múnoz–Martín, 2020). Then, the difference in composition of the volcanoes of the "Alkalibasaltic Volcanic Province" defined by Kroonenberg et al. (1982a), and their structural arrangement, would reflect the complexity of the tectonic and petrological processes that control the origin and rise of the magma that form the monogenetic volcanoes in this region.

Additional stratigraphic, structural, and geophysical studies, complemented with systematic sampling for geochemical analysis for the identified volcanoes, will clarify on the origin of volcanism in this area and the delimitation of the fields. At the moment there are no chemical analyzes available for many volcanoes in the Isnos sector, nor for the Santa Leticia, Marsella, and La Palma Volcanoes, in the Moscopán area, nor for those of El Carmen and Granates, located between this field and that of Isnos–San Agustín, that allows defining their affinity.

The Guamuez–Sibundoy volcanic centers may represent a retro–arc volcanism. The basaltic composition is assumed from the few petrographic and chemical descriptions (Küch, 1892; Núñez, 2003; Rodríguez & González, 2004), while its monogenetic character is inferred by the geomorphological expression described by Buchelli (1986), Robertson et al. (2002), and Flórez (2003). The geochemical composition of two samples indicates that they are ultramaphic, nephelinite basalts (due to their normative nepheline), like the Acevedo basalts (Rodríguez & González, 2004). This volcanism could also be related to the complex configuration of the southern part of Colombia and northern Ecuador. The lack of more precise data on this sector prevents any more specific hypothesis about its origin and its relationship with the Alkalibasaltic Volcanic Province, as well as the delimitation of a monogenetic volcanic field.

The monogenetic volcanism identified in the MeMVF corresponds to basalts and basaltic andesites of the high magnesium calc–alkaline series (Figure 29). The Guacharacos and Tabor Volcanoes are in the interception zone of the Ibagué (SW–NE) and the Buenos Aires (SE–NW).

The volcanoes of the MeMVF are related to subduction, however, the presence of basalts and andesites high in magnesium indicates primary magmas of mantle origin (i.e., Bryant et al., 2010; Calmus et al., 2003; Hoang et al., 2009; Kelemen et al., 2014; Nauret et al., 2012; Negrete–Aranda & Cañón–Tapia, 2008; Pallares et al., 2007; Wood & Turner, 2009), which may be caused by partial fusion of the lithospheric mantle or material of asthenospheric origin, the most common parent material being peridotite or eclogite, that is, they would have a different origin than the active volcanoes of the north segment of active volcanism in Colombia.

The ascent of the primary magmas of the known volcanoes of the field, must then have been through the Ibagué Fault Zone and its satellite faults, taking into account that no major tectonic structure associated with the Nazca subducting plate has been reported that could facilitate the rise of the magma; however, it should be noted that this volcanism is located at the northern limit of the gap between the active central and northern volcanic segments of the Central Cordillera.

10. Conclusions

Monogenetic basaltic volcanism in Colombia has been scarce studied. In this chapter geological, morphological, and geochemical information of groups of volcanoes located on the eastern flank of the Central Cordillera of Colombia and the UMV was presented, based on existing works and new data collected in field work carried out for this project.

Four monogenetic volcanic fields are defined and a group to the south, located in the rear–arc position, of the three main fields defined segments of the active volcanic front. Primary magmas, observed in these small–volume basaltic systems, range from silica–subsaturated nephelinites through alkaline basalts and basalts to silica–saturated, transitional, and silicic basalts.

The volcanoes, related to the southern volcanic segment, are the least known and with the available data it is not possible to have further conclusions about their origin. However, attention is drawn to allusions to possible historical activity of some of them in this sector.

The rear–arc volcanoes of the central volcanic segment, initially called "Alkalibasaltic Volcanic Province", are made up of at least 35 volcanic structures that are distributed in three clusters, close to each other that form the volcanic fields of Moscopán, Isnos–San Agustín, and Acevedo. They correspond to small volcanoes, mainly scoria cones with associated lavas and some pyroclastic rings and effusive centers, whose morphology indicates an activity for a few million years for the volcanic field. The morphological parameters used for their characterization indicate various intervals of relative ages between the eruptive centers, which must be verified through geological dating.

The main volcanic products of the volcanic fields in the region of the UMV are the lava flows formed by olivine basalt, basaltic andesites with phenocrysts of plagioclase, pyroxene and olivine, and andesite with phenocrysts of plagioclase and pyroxene. Most of the lavas have low SiO_2 content, high alkalis, LILE and LREE enrichment. The volcanoes of the Acevedo and Isnos–San Agustín Volcanic Fields have high numbers of Mg and high contents of Cr, Ni, and TiO_2, which suggests that they crystallized directly from the primary magma, while most of the rocks of MMVF present a subalkaline affinity and present a close relationship space with the volcanic centers of the Coconucos Volcanic Chain, which present an adakitic tendency in their products.

The Acevedo and Isnos–San Agustín Volcanic Fields are associated with strike–slip faults of the eastern fault front, considered the South American Plate boundary with the Andean Microplate, located in pull–apart sectors of the Algeciras Fault and other right–lateral faults associated. The fields are related to intraplate volcanism associated to extension, while those of the MMVF have a NW–SE structural control sub–parallel to the CVCh.

The available data show some similarities in composition between products of some volcanoes of this group or a transitional character between them; however, there are many volcanoes that do not have any type of analysis, such as those that are geographically located between the Moscopán and Isnos–San Agustín Volcanic Fields, which is necessary to better define the fields and the tectonic relationships between them.

In the region of the so–called Acevedo lavas, very well–preserved monogenetic volcanoes were identified indicating recent ages for this volcanism, therefore it is suggested to review the reported age of 31.2 ± 2.7 Ma, obtained by Kroonenberg et al. (1982a), in order to verify the relationship of the volcanoes with the most recent tectonics.

The name of the MeMVF is proposed for the monogenetic volcanoes found in the northern segment of volcanism. They are basalts and basaltic andesites high in magnesium of calc–alkaline character, which represent primary magmas. Unlike the fields in the UMV, this volcanism does not appear to be directly linked to plate boundary processes.

In the proposed monogenetic volcanic fields may be many more unidentified volcanic vents.

This chapter is the result of initial interdisciplinary project carried out by the Dirección de Geociencias Básicas of the Servicio Geológico Colombiano in order to understand small–volume volcanism in Colombia: Its characteristics, age, activity rates, distribution, tectonic relationships, and origin, among others, and thus appropriately define the basaltic monogenetic volcanic fields and its relationship with the evolutive history in the country. The future research will be focus on the basis for the volcanic monitoring and the hazard assessment in populated areas where the monogenetic volcanism develops.

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Explanation of Acronyms, Abbreviations, and Symbols:

AMVF	Acevedo Monogenetic Volcanic Field
ANVZ	Andean North Volcanic Zone
AVP	Alkalibasaltic Volcanic Province
CC	Central Cordillera
CVCh	Coconucos Volcanic Chain
EC	Eastern Cordillera
HFSE	High field strength elements
HREE	Heavy rare earth elements
IGAC	Instituto Geográfico Augustín Codazzi
ISMVF	Isnos–San Agustín Monogenetic Volcanic Field
LILE	Large ion lithophile element
LOI	Loss on ignition
LREE	Light rare earth element
MMVF	Moscopán Monogenetic Volcanic Field
MeMVF	Metaima Monogenetic Volcanic Field
MORB–OIB	Mid–ocean ridge basalt –Ocean island basalt
N–MORB	Normal mid–oceanic basalts
REE	Rare earth element
SEM	Scanning electron microscope
SGC	Servicio Geológico Colombiano
SKS	Unspecified S wave traversing the core as P
SVC	Sotará Volcanic Complex
UMV	Upper Magdalena Valley
WC	Western Cordillera

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María Luisa MONSALVE–BUSTAMANTE 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.

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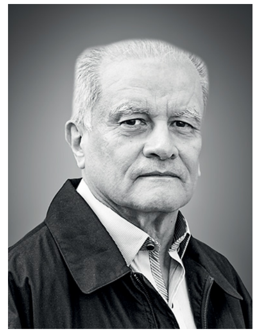

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