

Geological mapping of intrusive rocks: a case study in the Garzón region, the Eastern Cordillera of the Colombian Andes

Mapeamento geológico de rochas ígneas: Um estudo de caso na região de Garzón, Cordilheira Oriental dos Andes Colombianos

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Abstract

Jurassic granites (*sensu lato*) and related rocks are the most abundant rocks cropping out in the Eastern Cordillera of Colombia in the northern Andes. We present an attempt to map and characterize in detail the petrographic diversity of the Jurassic granites and related subvolcanic rocks emplaced in the Garzón region, southernmost the Eastern Cordillera. We also provide new geological maps for the Algeciras and Altamira Plutonic Massifs based on descriptive concepts of the petrographic facies and facies associations and detailed petrographic and mineralogical characterizations of the observed granite types. Eight plutonic and three subvolcanic petrographic facies or facies associations were mapped in the Algeciras Plutonic Massif, and another five in the Altamira Plutonic Massif. Hornblende biotite granites (syeno- and monzogranites) are the main plutonic types constituting the first massif, while leucogranites prevail in the second massif; a zoned facies distribution was mapped in the Algeciras Plutonic Massif. Felsic porphyries (dacite and rhyolite) crop out as minor irregular intrusive bodies or dikes and mafic-intermediate syn-plutonic dikes (mostly microdiorites) cross cut the main plutonic rocks in both massifs. Geological and petrographic characteristics (e.g. micrographic textures) suggest relatively shallow emplacement levels for the plutonic rocks as well as slightly high uplift and erosion rates at the north of the studied area. Local penetrative solid-state planar structures and dike orientations conform with dextral strike-slip movements along the SSW-NNE trending Algeciras Fault System in a transpressional regime associated with a major compressive and oblique convergence in Jurassic ages.

Keywords: Granite mapping; Petrographic facies; Algeciras Plutonic Massif; Altamira Plutonic Massif; Colombian Eastern Cordillera.

Resumo

Granitos Jurássicos (*sensu lato*) e rochas relacionadas são as rochas mais comuns que afloram na Cordilheira Oriental da Colômbia no norte dos Andes. Apresenta-se um mapa e uma caracterização detalhada da diversidade petrográfica dos granitos jurássicos e rochas subvulcânicas relacionadas que afloram na região de Garzón, extremo sul da Cordilheira Oriental. Elaboraram-se novos mapas geológicos para os Maciços Plutônicos de Algeciras e Altamira, baseados nos conceitos descritivos de fácies e associações de fácies petrográficas, petrografia detalhada e caracterização mineralógica dos tipos de granitos observados. Oito fácies petrográficas ou associações de fácies plutônicas e três subvulcânicas foram reconhecidas e mapeadas no Maciço Plutônico de Algeciras e outras cinco no Maciço Plutônico de Altamira. Hornblenda biotita granitos (sieno- e monzogranitos) predominam no primeiro maciço, enquanto leucogranitos são predominantes no segundo. Um padrão zonado de distribuição de fácies foi mapeado no Maciço Plutônico de Algeciras. Corpos menores e/ou diques de pórfiros félsicos (dacitos e riolitos) e diques máficos-intermediários sin-plutônicos (principalmente microdioritos) cortam as principais rochas plutônicas nos dois maciços. Características geológicas e petrográficas (e.g. texturas micrográficas) sugerem níveis de colocação relativamente rasos para as rochas plutônicas e soerguimento e erosão levemente mais acentuados na região norte da área estudada. Estruturas planares de deformação em estado sólido e a orientação dos diques mapeados são compatíveis com movimentações dextrais do Sistema de Falhas de Algeciras, orientado SSW-NNE, em um regime transpressivo, associado com importante compressão e convergência oblíqua durante o Jurássico.

Palavras-chave: Mapeamento de granitos; Fácies petrográfica; Maciço Plutônico de Algeciras; Maciço Plutônico de Altamira; Cordilheira Oriental da Colômbia.

INTRODUCTION

Geological mapping and the stratigraphic nomenclature of igneous intrusive rocks are still controversial issues in geosciences and several authors have proposed specific nomenclatures trying to unify concepts for intrusive rocks in the last decades (*e.g.*, Bateman and Dodge, 1970; Cobbing et al., 1981; Cobbing, 2000; Klomínský et al., 2010; Ulbrich et al., 2001; and references therein), without a common consensus. For instance, the North American Stratigraphic Code (NACSN, 2005) defines a lithodemic unit as one made up by entirely intrusive, highly deformed, and/or highly metamorphosed rocks, and recognizes that this unit generally does not conform to the law of superposition. On the other hand, the International Union of Geological Sciences (Salvador, 2013) includes all of the characteristics above in lithostratigraphic units and the primary formal unit used to map, describe and interpret the geology of a region is the “formation”. Nevertheless, the minor subdivisions “member or bed” and “lithodem”, in the case of lithostratigraphic and lithodemic units, respectively, appear to be inappropriate to describe the detailed characteristics of intrusive igneous rocks. This appears also to be the case with the so-called units and superunits (Cobbing et al., 1981; Cobbing and Pitcher, 1972; Cobbing, 2000).

Ulbrich et al. (2001) proposed *plutonic facies* as a descriptive term to avoid some of the questions above. It is defined as the minor hierarchical level of an *informal* lithostratigraphic unit that can be recognized and described in hand samples and field outcrops based on their mineralogical, textural and structural properties, without *a priori* genetic implications. The term *facies association* was proposed by Vlach (1985, 1993) to group similar petrographic facies that should be mapped together, considering their distributions in relation to the mapping scale. In this sense, a petrographic facies or a facies association corresponds to a mapping unit (Ulbrich et al., 2001; Vlach, 1985, 1993).

Grouping mapping units into major stratigraphic units may be a difficult task when dealing with granitic and related rocks. Conventional mapping studies generally use terms such as “pluton”, “intrusion”, or “occurrence” or even petrographic names such as “granite” or “syenite” together with a geographic term (*e.g.*, Garzón Granite) in order to name an igneous intrusion or pluton, which represents a structurally coherent single- or multi-intrusive unit limited by well-established external contacts (Vlach, 1993). These units, based on their size, may be grouped within *batholiths*, *plutonic massifs* or *complexes*. These terms appear to be the most appropriated to describe the intricate magmatic intrusions with different compositions structures and ages that outcrop in Colombian Eastern Cordillera. On the other hand, in the Bohemian Massif, the term “massif” (most popular in the Czech literature) defines “a body of intrusive igneous rock

of at least 15 to 30 km in diameter occurring as a structurally resistant mass in an uplifted area that may have been a mountain core” (Klomínský et al., 2010). In this case, massif should be a hierarchical unit larger than pluton, in contrast with the most conventional literature (Cobbing, 1999; Cobbing et al., 1981; Cobbing and Pitcher, 1972; Ulbrich et al., 2001). According to the Czech nomenclature, magmatic bodies such as the studied Algeciras and Altamira may be considered as massifs. The qualifier “composite” may also be used to indicate compositional, spatial and time complexity in describing these magmatic bodies.

Jurassic granitic magmatism (*sensu lato*) is widespread in the Central and Eastern cordilleras of the Colombian Andes, cropping out in an area of approximately 32,500 km² and including several major occurrences (*e.g.*, Ibagué and Segovia batholiths). However, systematic geological mapping of such rocks at an appropriate scale is still scarce, and there are several local nomenclature issues. In the Garzón region (Eastern Cordillera), the large (> 100 km²) Altamira and Algeciras intrusive bodies have been alternatively named as “batholiths”, “stocks”, “monzogranites”, or even “granites” (*e.g.*, Arango et al., 2015; Rodríguez et al., 2015b; Velandia et al., 2001). Importantly, all plutonic occurrences are constituted by several field-recognizable granite varieties, which can be properly mapped on a 1:50,000 scale, as individualized petrographic facies or facies associations. In this contribution, we present geological maps of the Algeciras and Altamira Plutonic Massifs in the Colombian Eastern Cordillera, attempting to organize and define granitic mapping units in the Garzón region to be improved with further fieldwork.

GEOLOGICAL BACKGROUND

Regional context

Colombia, NW South America, presents two main contrasted geomorphological regions. To the east, in the Orinoco and Amazonian plane areas, Meso- to Neoproterozoic igneous and metamorphic rocks are covered by Paleozoic, Mesozoic and Cenozoic sedimentary rocks and sediments, while westwards, the mountain ranges of the Colombian Andes comprise the Western, Central and Eastern cordilleras, each other isolated by inter-Andean basins filled in with Paleozoic to Cenozoic volcano-sedimentary rocks. The studied Garzón area is located to the south of the Eastern Cordillera (Figure 1), a highland area constituted by both Andean intrusive and their Meso- to Neoproterozoic country rocks, as in other areas within this Cordillera (*e.g.*, Santander, Floresta and Quetame) and the Santa Marta area to the north of Colombia. The main geological features of the studied area are described in the following.

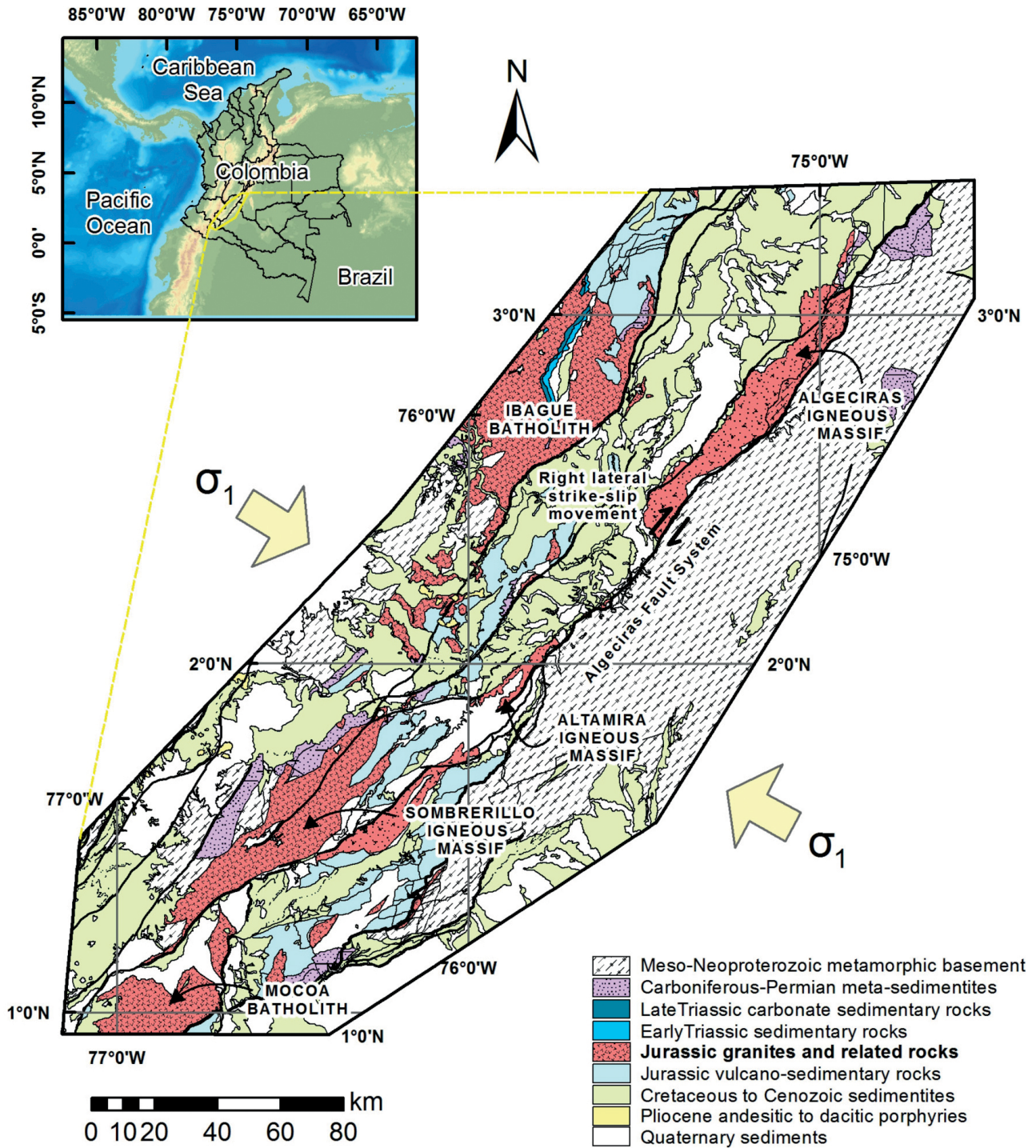


Figure 1. Simplified geological map of the Garzón area in the Colombian Eastern Cordillera showing the Jurassic Plutonic Massifs (red), the volcano-sedimentary Saldaña Formation (blue), Meso-Neoproterozoic metamorphic basement (white with crosses), Paleozoic metasediments (purple), Cretaceous and Cenozoic sedimentary rocks (gray) and Quaternary sediments (white). The main plutonic massifs of Algeciras, Altamira and Sombrerillo are indicated. Other Jurassic igneous occurrences such as the Ibagué and Mocoa Batholiths (to the west and to the south, respectively) are also indicated. Yellow arrows indicate the main strain (σ_1). Algeciras Fault System limits the Jurassic igneous rocks with the metamorphic basement.

Country rocks comprise a variety of sedimentary- and igneous-derived medium- to high-grade metamorphic rocks (charnockites, gneisses, amphibolites, and granulites), as well as migmatites (Jiménez Mejía et al., 2006). These ancient rocks correlate with those cropping out in the Putumayo Basement, Las Minas and Macarena mountain ranges, and with those in the main metamorphic complexes from Mexico and Central America (e.g., Oaxaca and Guichicovi), formed during the Putumayo-Oaxaca Orogeny at 1.0–1.3 Ga (Ibanez-Mejia et al., 2011).

The Paleozoic, Carboniferous to Permian and Ordovician sedimentary rocks are made up by strongly faulted marine sequences that form isolated outcrops (Mojica et al., 1988; Moreno-Sánchez et al., 2008; Villarroel et al., 1997). Mojica et al. (1988) and Núñez (2003) suggested that Andean Jurassic granitic rocks had intruded them. These sequences were later covered by volcano-sedimentary sequences of the Saldaña Formation (Mojica et al., 1988) by 186 ± 2 Ma (Zapata et al., 2016), which are discordant in relation to the Andean granitic rocks in this area.

Granitic rocks from the Algeciras and Altamira Plutonic Massifs emplaced by 169 to 179 Ma (U/Pb in zircon, Bustamante et al., 2010; Rodríguez et al., 2018) and their intrusion has been related to a magmatic arc developed during oceanic crust subduction beneath the northwestern South American Plate (Aspden et al., 1987; Aspden and McCourt, 1986; Bayona et al., 2006; Bustamante et al., 2016; Cochrane et al., 2014a; McCourt et al., 1984; Spikings et al., 2015). This orogeny is widespread distributed in the western side of North, Central and South America (Aspden et al., 1987; Jaillard et al., 1990; Pindell and Dewey, 1982; Ross and Scotese, 1988); nevertheless, some of its characteristics remain unclear. For instance, subduction regimes change from Late Jurassic to Early Cretaceous (Burke, 1988; Bustamante et al., 2016; Pindell et al., 2006), and there was a significant decrease in the overall magmatic activity (Bustamante et al., 2016; Villagómez et al., 2011), especially in the Eastern Cordillera.

A marginal Cretaceous basin was developed in the Eastern Cordillera area in association with a protracted extensive/extensional regime (Cooper et al., 1995; Sarmiento-Rojas et al., 2006). The first Cretaceous sedimentation in the studied area occurred during Aptian and Albian times and crops out into the Upper Magdalena River basin, covering the Saldaña Formation (Cooper et al., 1995; Velandia et al., 2001). Sedimentation appears to have remained relatively constant until the early Cenozoic, when subduction processes increased and the previous back-arc basin settings changed to a foreland basin (Cooper et al., 1995). By this time, younger magmatic arcs developed in the Central and Western cordilleras (Aspden et al., 1987; Bustamante et al., 2016; Cochrane et al., 2014b; McCourt et al., 1984; Spikings et al., 2015), while in the Eastern Cordillera, the magmatic activity disappeared, perhaps due to a slab roll back process,

which moved the subduction front westward (Cochrane et al., 2014). Subduction and related magmatism were most likely related then to the evolution of the Caribbean Plate and the accretion of oceanic terranes in northwestern South America (Pindell et al., 2005; Pindell et al., 2006; Spikings et al., 2015). Foreland basin sedimentation continues, accompanied by deformation and thrust faulting in the Magdalena Valley basin, which unconformably overlays upper Eocene sediments, generating the upper Oligocene angular unconformity (Schamel, 1991). The most significant deformation event in the Eastern Cordillera occurred by the Miocene (Cooper et al., 1995; Schamel, 1991), uplifting it to expose the main Jurassic granitic intrusions and their country rocks.

Previous geological studies

Grosse (1930) carried out the first geological studies on Garzón Jurassic granitic rocks in the Eastern Cordillera. The author described several elongated granitic bodies with relatively homogenous compositions, varying from granodiorite to diorite, as well as late lamprophyre and aplite dikes cross-cutting metamorphic country rocks. Based on stratigraphic relations, a pre-Cretaceous age was attributed to them.

The main petrographic features of these intrusive rocks were presented three decades later by Radelli (1962a, 1962b, 1962c). The author classified them as “plutons” and recognized amphibolitic-micaceous syenites in the Suaza and Altamira Plutons, as well as granites in the Hobo-Algeciras Pluton and porphyritic granites in the Garzón Pluton. He emphasized that amphibole-bearing microdiorite, aplite and pegmatite dikes intrude the granites in all plutons, which, according to him, were formed during the same magmatic event, given their common mineralogical associations and homogeneous structures.

Recent mapping efforts for the Eastern Cordillera areas at 1:100,000 and 1:300,000 scales were presented by several authors (Acosta and Osorno, 1999; Arango et al., 2015; Cárdenas et al., 2002, 2003; Marquínez and Velandia, 2001; Morales et al., 2001; Núñez, 2003; Núñez and Gómez, 2002b, 2002c; Rodríguez et al., 1998, 2003a, 2003b, 2015a, 2015b; Velandia et al., 1999). All of them describe plutonic rocks as undifferentiated, homogeneous “batholiths” or “stocks” and most rock descriptions were limited to their general composition, without further refinements. Rodríguez et al. (2018) recognize many Jurassic intrusive “stocks” and “batholiths” to the west and east of the Upper Magdalena Valley, with contrasted ages and rock varieties, but did not specify their distribution, abundance or structural relationships.

METHOD

Geological mapping of Algeciras and Altamira granitic rocks was carried out according to the concepts of petrographic

plutonic facies and facies association, as introduced by Ulbrich et al. (2001) and Vlach (1985, 1993). Each plutonic facies was defined according to their mineralogical, textural and structural properties, as detailed by these authors. Late refinements, particularly concerning accessory mineralogical contents, their distributions and a proper International Union of Geological Sciences (IUGS) petrographic classification was performed through thin section analyses under a petrographic microscope at the Optical Microscopy Laboratory of the GeoAnalítica USP core facility.

The fieldwork was performed in several campaigns during 2010–2013 by the main author and other geologists with the logistical support of the Colombian Geological Service (*Servicio Geológico Colombiano* — SGC) and later in 2014, during his doctoral studies at São Paulo University. Topographic (1:100,000) and previous geologic (1:100,000) maps (Acosta and Osorno, 1999; Cárdenas et al., 2002, 2003; Morales et al., 2001; Núñez, 2003; Núñez and Gómez, 2002a; Rodríguez et al., 1998; Velandia et al., 1999, 2001) were used as field references. The final maps are presented on a 1:50,000 scale and are based on a data set that includes more than 300 rock outcrops and ca. 250 petrographic thin sections.

The data set was limited to variable extents due to the huge topography, extensive vegetation cover and local intense weathering, which avoid good rock exposures and make field access difficult. Therefore, most contacts between intrusive plutonic and subvolcanic facies and between intrusive

rocks and their metamorphic envelopes or sedimentary cover were not mapped with the desired detail. Such contacts, as well as the main regional faults and/or lineaments, were drawn mainly based on the Global Digital Elevation Model (GDEM; NASA, 2016). Likewise, minor intrusive or subvolcanic igneous occurrences, such as dikes and plugs are represented solely as illustrative at the adopted scale.

RESULTS

The studied rock reveals textural and mineralogical variations which could be recognized in outcrops and/or hand samples and that could be better represented in geological maps. Most mapped granitic varieties present light grayish or light to dark pink colors and, as relevant, the darkest pinkish colors are closely associated with zones presenting variable evidence of late hydrothermal imprint. The main features of the recognized facies/facies associations are presented next. Table 1 summarizes these characteristics while representative modal data are listed in Table 2.

The Algeciras Plutonic Massif

The Algeciras Plutonic Massif is elongated in the SW-NE direction, with ca. 5–10 km width and 50 km length, occupying an exposed highland area close to 500 km² (Figure 2).

Table 1. Summary of facies and facies association characteristics of the Algeciras and Altamira plutonic massifs. Area(%) is the outcrop area in relation to the total area of the Massif. Mineral abbreviations according Whitney and Evans (2010).

Facies/facies associations	Area (%)	Texture	Color Index (CI)	Mafic phases	Accessory phases	Observations
Algeriras Plutonic Massif						
<i>Hornblende biotite granites</i>	60	Inequigranular hypidiomorphic, medium- to coarse-grained	10 ≤ CI ≤ 15	Hlb + Bt	Ttn + Aln + Mt + Il + Ap + Zrn	Massive structure dominant, mafic-intermediate syn-plutonic dike swarms, mafic microgranular enclaves
<i>Leucogranites</i>	30	Inequigranular to equigranular, medium-grained	CI ≤ 5	Bt	Ttn + Aln + Fe - Ti oxides + Ap + Zrn	Slightly planar orientations.
<i>Hornblende monzogranites</i>	< 5	Inequigranular, medium- (predominant) to coarse-grained,	CI ≤ 9	Hlb + cpx (relicts)	Ttn + Mt + Il + Ap + Zrn ± Aln	Massive, slightly pervasive hydrothermal alteration with epidote-group minerals, chlorite, white micas and some carbonate. Hydrothermal alteration with epidote-group minerals, titanite and opaque phases as mineral aggregates filling in rock interstices and fractures.
<i>Hornblende biotite granodiorites</i>	< 5	Inequigranular, medium- to coarse-grained	Up to 20	Hlb + Bt	Ttn + Ap + Zrn ± Opaque minerals	

Continue...

Table 1. Continuation.

Facies/facies associations	Area (%)	Texture	Color Index (CI)	Mafic phases	Accessory phases	Observations
<i>Biotite hornblende monzogranites</i>	< 5	Inequigranular, medium- to to coarse-grained	$13 \leq CI \leq 15$	Bt + Hlb	Ttn + Aln + Fe-Ti oxides + Ap + Zrn	Among the hydrothermal phases, prehnite appears with chlorite substituting for biotite.
<i>Biotite monzogranites</i>	< 5	Equigranular, medium- to to coarse-grained	$5 \leq CI \leq 10$	Hlb	Fe-Ti oxides + Ttn + Aln + Ap + Zrn	
<i>Mylonitic biotite monzogranites</i>	< 1	Medium-grained	$5 \leq CI \leq 10$	Bt	Fe-Ti oxides + Ttn + Aln + Ap + Zrn	Well-developed solid-state foliation, porphyroblast with kinematic indications
<i>Micrographic leucomonzogranites</i>	< 1	Medium-grained,	$CI \leq 3$	Bt	Fe-Ti oxides + Ttn + Ap + Zrn (rare)	Quartz-alkali feldspar micrographic intergrowths.
<i>Rhyolite porphyries</i>	< 1	Glomeroporphyritic in a fine-grained matrix	$CI < 5$	Hlb + Bt	Fe-Ti oxides + Ttn + Ap + Zrn	Alkali feldspar + quartz micrographic intergrowths and spherulites.
<i>Mafic-intermediate dikes</i>	< 1	Andesites: porphyritic in a fine-grained/ aphanitic matrix. Microdiorites: equigranular, fine- to medium-grained	$30 \leq CI \leq 50$	Hlb + Bt	Mt + Il + Ttn + Ap	Occur as two main dike swarms trending N40-60°E/50-75°SW and N40-60°W/60-80°SW, associated with mafic microgranular enclaves. The andesites present a trachytic-like texture.
<i>Felsic dikes</i>	< 1	Inequigranular, fine- to medium-grained	$CI < 5$	Hlb + Bt	Fe-Ti oxides + Ttn + Ap + Zrn	Intrude the biotite hornblende monzogranites along a NW trend, similar to the mafic-intermediate dikes
Altamira Plutonic Massif						
<i>Leucomonzogranite facies association</i>	70	Inequi-/ equigranular hypidiomorphic, fine- to medium-grained	$CI < 5$	Bt	Aln + Ap + Zrn + Fe-Ti oxides + Py	A mylonitic variety, with alkali feldspar and plagioclase porphyroclasts, crops out close to the eastern tectonic contacts.
<i>Hornblende biotite granodiorite facies association</i>	20	Inequigranular, fine- to medium-grained	$10 \leq CI \leq 20$	Hlb + Bt	Ttn + Aln + Mt + Il + Ap + Zrn	Massive. chlorite usually replaces amphibole and biotite. Epidote-group minerals, chlorite, carbonate, albite, and sericite are hydrothermal minerals.
<i>Hornblende monzodiorite facies association</i>	< 10	Equigranular, medium- to coarse-grained	$15 \leq CI \leq 25$	Hlb	Mt + Il + Ap + Ttn + Zrn	Massive
<i>Andesite and/or microdiorite dikes</i>	< 1	Intergranular, fine-grained	$30 \leq CI \leq 50$	Hlb + Bt	Mt + Il + Ap + Ttn + Zrn	Slightly foliated, as syn-plutonic dikes and mafic microgranular enclaves, often associated with the porphyritic rhyolites
<i>Rhyolite porphyry dikes</i>	< 1	Porphyritic in a very fine-grained matrix	$CI \leq 5$	Hlb	Ttn + Opaque phases	Quartz-alkali feldspar micrographic intergrowths; quartz phenocrysts with embayments or skeletal

Most contacts of the intrusive rocks are tectonics: contacts with Cretaceous rocks of the Magdalena Basin are given by local fault systems, while the Algeciras Fault System, a major and broad deformation zone, limits the intrusive rocks with the high-grade metamorphic country rocks to the east (Figure 2). We were able to identify and map eleven plutonic and subvolcanic facies or facies associations (Figure 2, Table 1); which are briefly described in the following. Representative modal data are given in Table 2 and represented in the QAP modal diagram in Figure 3.

Hornblende biotite granite facies association

This facies association is predominant over the entire granitic massif, corresponding to 60% of the total mapped area of the massif. Its best exposures occur along the Neiva River, close to the Algeciras-Campo Alegre highway, and to the northern mapped area. The rocks are medium- to coarse-grained and present an inequigranular hypidiomorphic texture (Figure 4). In general, alkali-feldspar modal contents are similar or somewhat higher than plagioclase and, according to the IUGS nomenclature (Le Maitre, 2002), they correspond to monzogranites and syenogranites (Figure 3). They are leucocratic, $10 < \text{Color Index (CI)} < 15$ with similar modal proportions of amphibole and biotite (Table 2). Under the microscope, the plagioclase is andesine and the alkali feldspar (orthoclase and/or low microcline) does not present detectable cross-hatched twins; some samples have large alkali-feldspar crystals (up to 1 cm) with a poikilitic-like

texture given by a great number of euhedral plagioclase inclusions. The amphibole, with green to yellow-greenish pleochroic colors, corresponds to a calcic, hornblende-like variety. Biotite (brown-reddish) occurs as isolated crystals, as mafic clots, and occasionally substitutes for hornblende. Titanite, allanite, Fe-Ti oxides, apatite and zircon are common accessory minerals, which appear as isolated euhedral crystals or form small mafic clusters with the main mafic silicates (Figure 4B).

A typical feature of this facies association is the widespread occurrence of microdioritic enclaves with round, elongate or slightly irregular shapes, with diameters varying from several millimeters to tens of centimeters. The contacts with the granites are generally sharp (Figure 4C); some of them show a thin zone with aphanitic texture at their internal contacts, suggesting they were frozen against the host rock.

Leucogranite facies association

This is the second most abundant facies association mapped in the Plutonic Massif (ca. 30% of the total area), and crops out toward the central-east and southern areas. Slightly planar orientations, due mainly to solid-state deformation, are relatively common. They are medium-grained, slightly inequigranular to equigranular and hololeucocratic, with $\text{CI} < 5$; amphibole is absent. In the thin sections, plagioclase is oligoclase to andesine and shows some bent lamellae twins and alkali feldspar is a typical microcline, with well-developed cross-hatched twinning (Figure 4D). Quartz crystals have

Table 2. Modal compositions of representative rocks from the Garzón area, the Eastern Cordillera of Colombia. Mineral abbreviations according to Whitney and Evans (2010)

Sample	Massif	Facies	Felsic			Mafic			Accessory			Others					CI (%)			
			Kfs	Qtz	Pl	Bt	Hbl	Cpx	Ttn	Zrn	Ap	Aln	Chl	Sauss	Ser	Mus		Hem	Ep	Cal
GAR-350	Alg	L-SG	31	38	18	1.3	0.1	0	0.5	0.3	0.8	0.1	1.8	3.7	0.0	0.0	0.1	1.0	0.0	5
GAR-351	Alg	L-MG	29	31	32	1.9	0.4	0	0.4	0.3	0.6	0.1	1.4	0.4	0.0	0.0	0.0	0.1	0.0	5
GAR-352	Alg	L-MG	29	35	23	2.8	1.7	0	1.2	0.2	0.2	0.2	2.7	0.0	0.0	0.0	0.0	0.8	0.0	9
GAR-354	Alg	L-MG	32	41	25	0.3	0.0	0	0.1	0.0	0.1	0.1	0.4	0.1	0.0	0.5	0.0	0.0	0.0	1
GAR-356	Alg	MG	27	25	37	3.5	3.2	0	0.8	0.2	0.5	0.0	0.5	0.6	0.1	0.0	0.0	0.0	0.0	10
GAR-357	Alg	BH-MG	27	23	35	2.8	6.4	0	2.0	0.2	0.4	0.0	0.0	0.4	0.0	0.0	0.0	0.2	0.0	14
GAR-357	Alg	E-MD	0	1	49	20.2	20.7	0	0.5	2.5	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	45
GAR-360	Alg	BH-MG	30	24	30	4.0	4.8	0	1.6	0.1	0.6	0.0	0.1	3.2	0.0	0.0	0.0	0.0	0.0	14
GAR-371	Alg	BH-MG	27	21	40	4.5	4.9	0	0.2	0.2	0.0	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	13
GAR-384	Alt	L-SG	50	34	13	0.2	0.2	0	0.5	0.2	0.2	0.0	0.8	0.2	0.0	0.0	0.0	0.2	0.0	2
GAR-385	Alt	L-MG	31	32	25	4.3	1.4	0	1.4	0.2	0.3	0.0	0.0	1.5	0.0	0.0	0.0	0.3	0.0	9
GAR-386	Alt	HB-GD	17	23	48	4.5	1.9	0	0.6	0.2	0.2	0.0	0.6	1.0	0.0	0.0	0.0	0.2	0.0	10
GAR-388	Alt	H-MZ	24	3	46	0.0	10.5	0	2.5	0.8	0.7	0.1	4.3	0.0	0.0	0.0	1.8	0.4	0.1	19
GAR-394	Som	HB-MG	24	25	37	3.8	5.8	1.5	0.6	0.6	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	15

Alg: Algeciras; Alt: Altamira; Som: Sombrello; BQ-M OC: biotite quartz-monzodiorite with two pyroxenes; L-SG: leuco-syenogranite; BH-MG: biotite hornblende monzogranite; HB-GD: hornblende biotite granodiorite; MG: monzogranite; H-MZ: hornblende monzodiorite; E-MD: microdiorite enclave; Kfs: alkali feldspar; Qtz: quartz; Pl: plagioclase; Bt: biotite; Hbl: hornblende; Cpx: clinopyroxene; Ttn: titanite; Zrn: zircon; Ap: apatite; Aln: allanite; Mus: muscovite; Chl: chlorite; Sauss: saussurite; Ser: sericite; Hem: hematite; Ep: epidote; Cal: calcite; CI: color index.

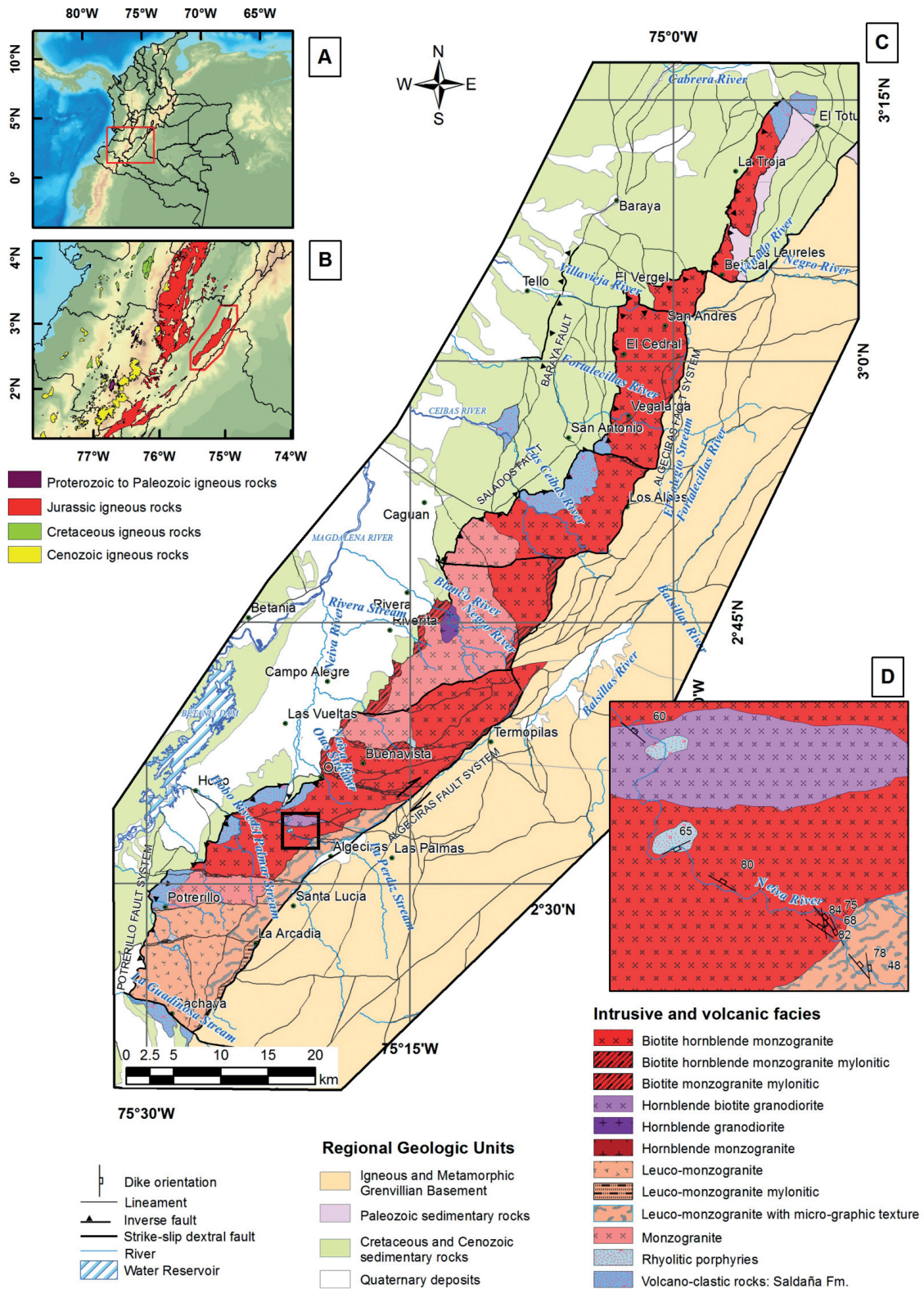


Figure 2. (A) Northwest South America, Central America and Caribbean showing Colombia and its internal departmental divisions. (B) Detail of the southern part of Colombian Andes with the locations of the igneous rocks discriminated as Jurassic (red) with Proterozoic to Paleozoic (purple), Cretaceous (green) and Cenozoic (yellow) intrusive rocks. (C) Petrographic facies map of the Algeciras Plutonic Massif. (D) Detail of structural data of dike orientation in the Neiva River.

undulatory extinction and sometimes appear as interstitial recrystallized aggregates. Biotite (brown to red-greenish by alteration) is mostly interstitial and appears accompanied by titanite, allanite, Fe-Ti oxides, apatite, and zircon.

Hornblende monzogranite facies association

Rocks from this association crop out to the northern massif areas, occupying less than 5% of the total area; the best exposures occur along the Las Ceibas River. They present pink to pink-grayish colors and are mostly constituted by massive, medium- (predominant) to coarse-grained inequigranular varieties with CI < 9 and alkali-feldspar dominant over plagioclase. Typical mafic mineral is amphibole, which appears mainly as isolated euhedral crystals; biotite is absent; quartz is interstitial to feldspar. In most samples, titanite is easily recognized in hand species. Under the petrographic microscope, the plagioclase (andesine) is strongly zoned, and the alkali feldspar has solely the simple Carlsbad twinning.

Calcic amphibole shows slight core to rim compositional zoning; some crystals may contain minute relicts of earlier colorless clinopyroxene, identified by its relatively high relief. Accessory phases occur as isolated euhedral crystals, as inclusions within felsic minerals or hornblende, or form mafic aggregates with the latter. They include titanite, allanite (occasional), Fe-Ti oxides, apatite, and zircon. Epidote-group minerals, chlorite, white micas, and some carbonates appear as secondary minerals.

Hornblende biotite granodiorite facies association

This facies association crops out in the west central area, with less than 5% of the total massif area, in the neighboring of the Blanco River. Typical varieties have similarities with the hornblende monzogranite facies association, described above; however, plagioclase is largely predominant over alkali feldspar, quartz contents are slightly lower and CI is higher (up to 20). Of importance, most examined outcrops and collected

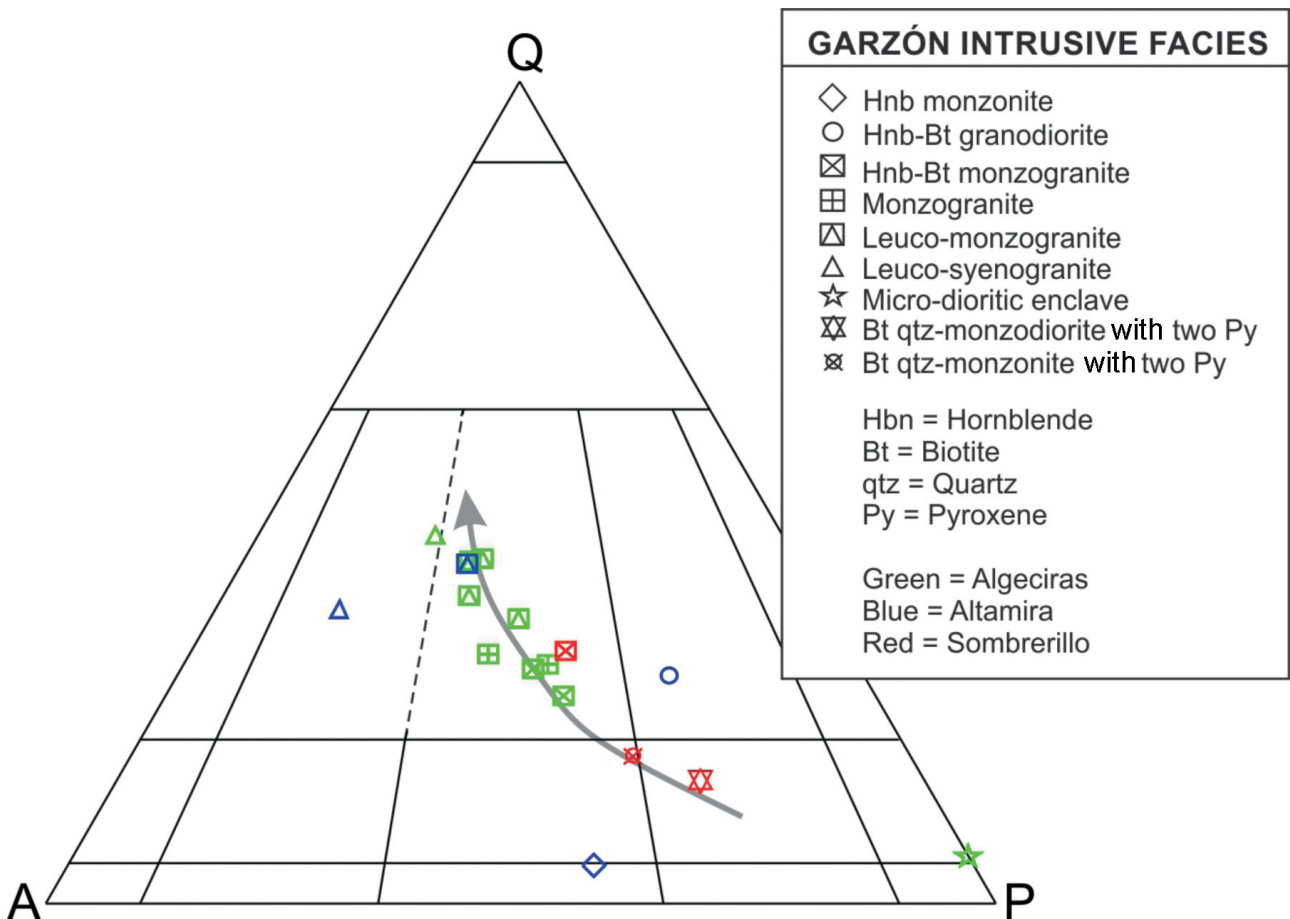
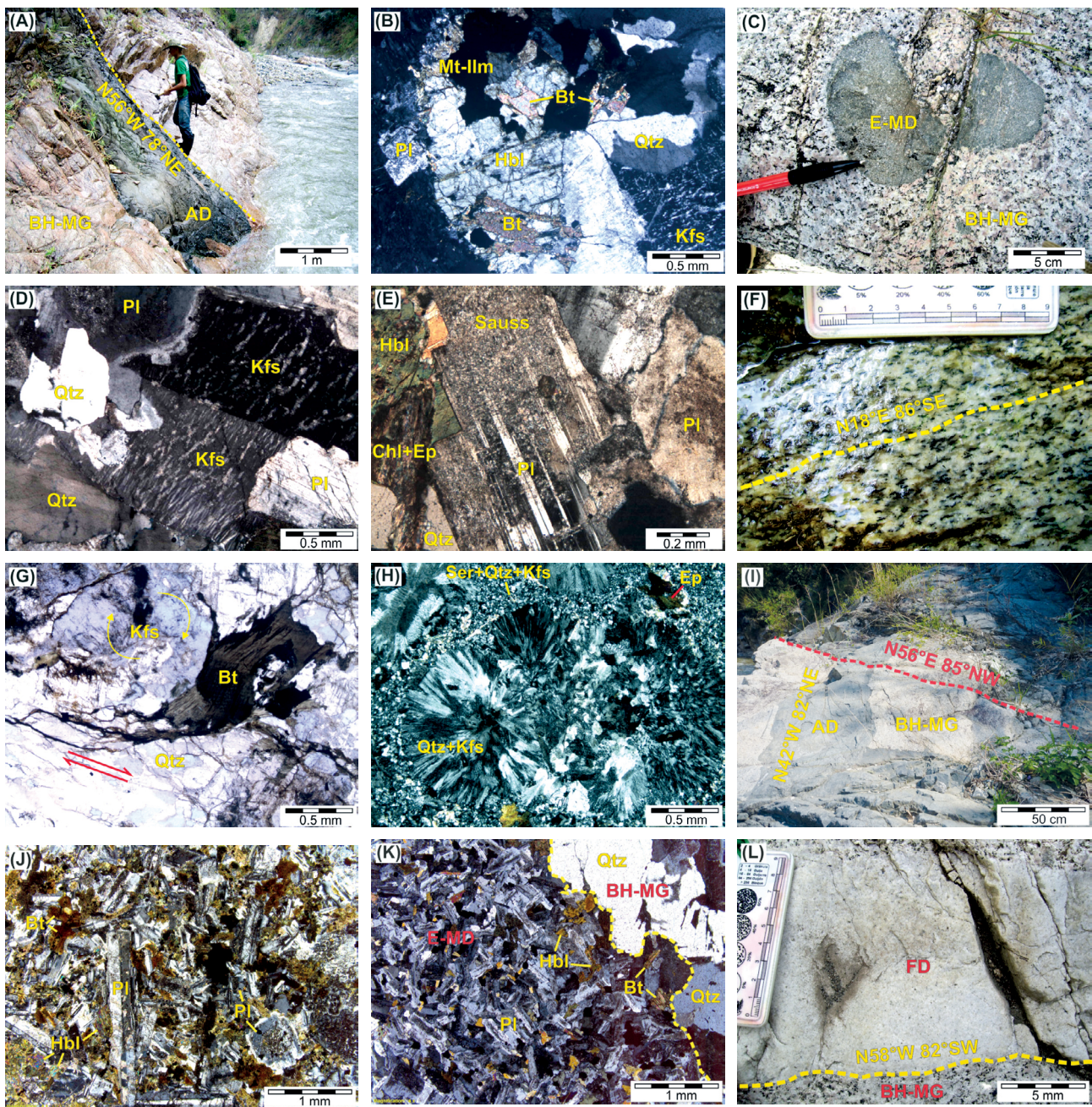


Figure 3. Modal Quartz-Alkali feldspar-Plagioclase (Q-A-P) classification diagram (Streckeisen, 1976). Green: Algeciras. Blue: Altamira. Red: Sombrerillo. The arrow represents the typical trend of the high-K calc-alkaline rocks associated with subduction in a continental margin (cf. Nédélec and Bouchez, 2015; Lameyre and Bowden, 1982).



Bt: Biotite; Chl: Chlorite; Ep: epidote; Hbl: hornblende; Kfs: alkali feldspar; Mt: magnetite; Il: Ilmenite solid solution; Pl: plagioclase; Qtz: quartz; Sauss: Saussurite aggregates; Ser: sericite.

Figure 4. Some geological and petrographic aspects of the Algeciras Plutonic Massif. (A) Biotite hornblende monzogranite (BH-MG) and andesitic dikes (AD). (B, D, E, H, J and K) Photomicrograph under cross and (G) parallel polarized light. (B) Biotite hornblende monzogranite, (C) mafic microgranular enclaves (E-MD) in the biotite hornblende monzogranite (BH-MG), and (D) leucomonzogranite. (E) Plagioclase altered to saussurite and calcic amphibole altered to chlorite and epidote in the hornblende biotite granodiorite. (F) Biotite monzogranite mylonitic facies (hand-sample), (G) detail under plane polarized light of biotite grain elongated and bent, alongside with rotated alkali feldspar crystal; red arrows indicate a dextral rotation sense. (H) Rhyolite with spherulitic intergrowths of quartz and alkali feldspar. (I) Andesite dikes fractured and truncated by minor local faults, intruding biotite hornblende monzogranites. (J) Strongly zoned plagioclases in microdiorite with pervasive alteration (K) interstitial amphibole grains between plagioclase laths of microgranular enclaves, and (L) felsic dikes (FD) of quartz and alkali feldspar.

samples show significant effects of hydrothermal imprints. Under the microscope, plagioclase (andesine) is altered to saussurite aggregates, and calcic amphibole to chlorite and epidote (Figure 4E). Hydrothermal epidote-group minerals, titanite and opaque phases, sometimes forming mineral aggregates filling in rock interstices or fractures, also appear in some thin sections. In the Picuma-Gallardo-Timaná road, these granodiorites are cross cut by andesite dikes striking N65°E 55°SE. Flow planar structures, given by the orientation of euhedral plagioclase crystals, are common, but they could rarely be properly measured.

Biotite hornblende monzogranite facies association

These rocks crop out to the northwest of the hornblende monzogranite exposure areas, along Las Ceibas River and neighboring and made up < 5% of the total massif area. In hand samples, they are inequigranular, medium- to coarse-grained, with $13 < CI < 15$. Plagioclase is predominant over alkali feldspar and, among the mafic minerals, hornblende is always associated with biotite. Quartz and biotite modal contents, as well as the biotite crystal sizes increase toward northwest, where eventually biotite becomes the main mafic phase. In thin sections, plagioclase shows compositional zoning from andesine to oligoclase; most crystal cores are saussuritic; the alkali feldspar is slightly cross-hatched twinned. Textural relations indicate that amphibole (zoned hornblende), in general the main mafic mineral, is partially replaced by primary biotite (Figure 4B). Typical primary accessory minerals are Fe-Ti oxides, titanite, allanite, apatite and zircon. Among the secondary phases, prehnite appears with chlorite, substituting for biotite.

Biotite monzogranite facies association

This association occurs in the northwestern-most area of the massif, with < 5% of the total area. The main differences in relation to the biotite hornblende monzogranites are the absence of amphibole, the modal predominance of alkali-feldspar over plagioclase, the low CI values (5–10) and the high values of modal quartz. Under the microscope, the plagioclase varies from andesine to oligoclase and perthitic alkali feldspar shows well-developed albite lamellae exsolution (Figure 4B).

Biotite monzogranite mylonitic facies association

Mylonitic biotite monzogranites ($5 < CI < 10$) crop out along most of the western massif external contacts, over < 1% of the total massif area. They present a well-developed foliation striking N18°E and dipping 86°SE (Figure 4F). Plagioclase and alkali feldspar porphyroclasts (sometimes slightly rotated, suggesting dextral relative moves) occur

in a matrix made up of recrystallized quartz and feldspars and oriented biotite crystals (Figure 4G).

Micrographic leucomonzogranite facies

This petrographic facies (< 1% of the massif area) occurs in the southern area of the eastern contacts of the massif. The best out crops appear along the Neiva River and neighboring areas. Samples are equigranular, medium-grained and hololeucocratic, (< 3) CI. Under the microscope, they are mainly constituted by medium-grained quartz-alkali feldspar micrographic intergrowths. Alkali feldspar is a typical microcline, and plagioclase is an oligoclase-andesine; biotite is the main mafic phase.

Rhyolite porphyries

These rocks appear as several minor and irregular bodies in the central and southern areas of the Algeciras Massif (ca. < 1% of the total area), intruding the hornblende monzogranites and leucogranite facies associations. Typical varieties have a porphyritic texture in a fine-grained matrix. The phenocryst population (30–50 %vol.) is constituted mainly by variable proportions of quartz, plagioclase and alkali feldspar; hornblende, biotite, Fe-Ti oxides and titanite also appear as phenocrysts in some samples. Quartz may appear as both embayed and skeletal phenocrysts. Under the microscope, rhyolites show glomeroporphyritic texture, given by plagioclase, alkali feldspar, and quartz phenocryst clots; the mesostasis made up by alkali feldspar + quartz micrographic intergrowths and spherulites (Figure 4H). Plagioclase and alkali feldspar phenocrysts are partially to fully substituted by saussurite and sericite, respectively.

Mafic-intermediate dikes

Andesite and/or microdiorite dikes (10 to 300 cm thick), often fractured and truncated by minor local faults (Figure 4I), intrude both biotite hornblende monzogranites and leucogranites in several mapped areas. There are two main dike swarms, trending N40-60°E/50-75°SW and N40-60°W/60-80°SW, respectively. Another dike set (N8-10°W/48-68°NE) occurs close to the Neiva River. Structural relationships between dikes, specially microdiorites, and host granites as well as the abundance of mafic microgranular enclaves with similar mineral composition, indicate they are syn-plutonic.

Andesites and microdiorites are compositionally similar; the main differences are in their textures. Andesites are porphyritic and present a very fine-grained or aphanitic matrix, while microdiorites are fine- to medium-grained and almost equigranular. In thin sections, andesites present a trachytic-like flow texture with zoned plagioclase (andesine to

labradorite) and amphibole phenocrysts (up to 0.5 mm) in a matrix consisted of plagioclase laths, amphibole, biotite, some Fe-Ti oxides, titanite, and minor quartz. Microdiorites have an equigranular hypidiomorphic texture and strongly zoned plagioclase laths (Figure 4J). Biotite content varies to a significant extent, from ca. 5 to > 20 vol%), and amphibole may preserve colorless, corroded, clinopyroxene crystals.

The closely associated mafic microgranular enclaves correspond to quartz diorites and quartz monzodiorites, with an intergranular-like texture given by strongly zoned plagioclase laths (mainly andesine) evenly distributed, with calcic amphibole filling in their interstices (Figure 4K). Minor and accessory minerals are biotite, alkali feldspar, quartz, opaque minerals, titanite and apatite.

Felsic dikes

Rhyolite or microgranite dikes intrude biotite hornblende monzogranites in some places. They are oriented along a NW trend, as part of the mafic-intermediate dikes. The rocks present fine- to medium-grained inequigranular textures (Figure 4L) and are hololeucocratic ($CI < 5$). Under the microscope, they show alkali feldspar (microcline) and quartz intergrowths and minor plagioclase (oligoclase). Quartz has undulatory extinction. Mafic minerals are scarce and include amphibole and biotite. Fe-Ti oxides, titanite, apatite and zircon are accessory phases.

The Altamira Plutonic Massif

The Altamira Plutonic Massif crops out to the south of the Algeciras Plutonic Massif, along a NE-SW main trend, covering an area of ca. 280 km² (Figure 5). The massif is covered by Cenozoic deposits of the Magdalena Basin westwards, while, to the east, the contact with high-grade country rocks is the Algeciras-Suaza Fault Zone, which is partially covered by late Quaternary sediments deposited along the Suaza River. Five facies or facies associations were identified and mapped in this plutonic massif (Table 1, Figure 5). They are briefly characterized as follows; representative modal data are presented in Table 2 and Figure 3.

Leucomonzogranite facies association

This association includes the most common rock varieties, occupying close to 70% of the total exposure area. It crops out in the southern area and is, in general, covered by dense vegetation. Most rock exposures are highly weathered and, so, fresh samples are relatively scarce. Typical leucomonzogranites show light grayish or white to pink colors (Figure 6A). They are constituted by hololeucocratic, equigranular to inequigranular, fine- to medium-grained

and massive varieties (Figure 6B). Biotite is the main mafic mineral (Figure 6C). The texture is hypidiomorphic in thin sections; alkali feldspar has poorly developed microcline twinning and is more abundant than plagioclase or quartz; aggregates of almost pure albite appear interstitial to oligoclase-andesine, which has a tabular habit and saussuritic core alteration. Quartz crystals are interstitial, anhedral, and present undulatory extinction. Primary accessory minerals are allanite, Fe-Ti oxides, apatite and zircon. Pyrite appears occasionally.

A mylonite variety, with alkali feldspar and plagioclase porphyroclasts, crops out in small exposure areas close to the eastern tectonic contacts.

Hornblende biotite granodiorite facies association

These rocks are subordinate to the main leucomonzogranites and appear as dikes or minor irregular bodies of ca. 10 to 200 m, occupying about 20% of the total massif area. They occur in the core areas and at the northwestern massif borders, exhibiting grayish to whitish color and $10 < CI < 20$. Under the microscope, the texture is hypidiomorphic, inequigranular; plagioclase, zoned from andesine (saussuritic cores in general) to oligoclase appears as tabular crystals and often shows corrosion figures. Alkali feldspar has slight cross-hatched twinning and contains some albite exsolution lamellae. Quartz is anhedral and interstitial and shows undulatory extinction. Mafic and accessory minerals appear as isolated crystals or crystal aggregates. Amphibole (hornblende) is the main mafic phase; biotite replaces amphibole. The accessory phases are titanite, allanite, Fe-Ti oxides, apatite and zircon. Chlorite usually replaces amphibole and biotite. Epidote-group minerals, chlorite, carbonate, albite, and sericite are secondary minerals.

Hornblende monzodiorite facies association

These rocks crop out in the central area of the massif (ca. < 10% of the total area). Most outcrops are discontinuous and limited, making it difficult to estimate their full extent. The rocks are massive, equigranular, and medium- to coarse-grained, with whitish to pinkish colors and $15 < CI < 25$. The texture is hypidiomorphic in thin sections, dominated by euhedral, tabular, plagioclase crystals, with minor, mainly interstitial, alkali feldspar (rarely up to 4 mm) and quartz. The modal results for this facies association plot as monzodiorites, close to the monzonite, quartz monzonite and quartz monzodiorite IUGS fields (Figure 3). Calcic amphibole (hornblende) occurs as isolated euhedral crystals or mafic clusters. Saussuritic plagioclase and amphibole strongly altered to chlorite are typical in the pinkish varieties. Fe-Ti oxides (magnetite and ilmenite), apatite, titanite and zircon are the main accessory minerals.

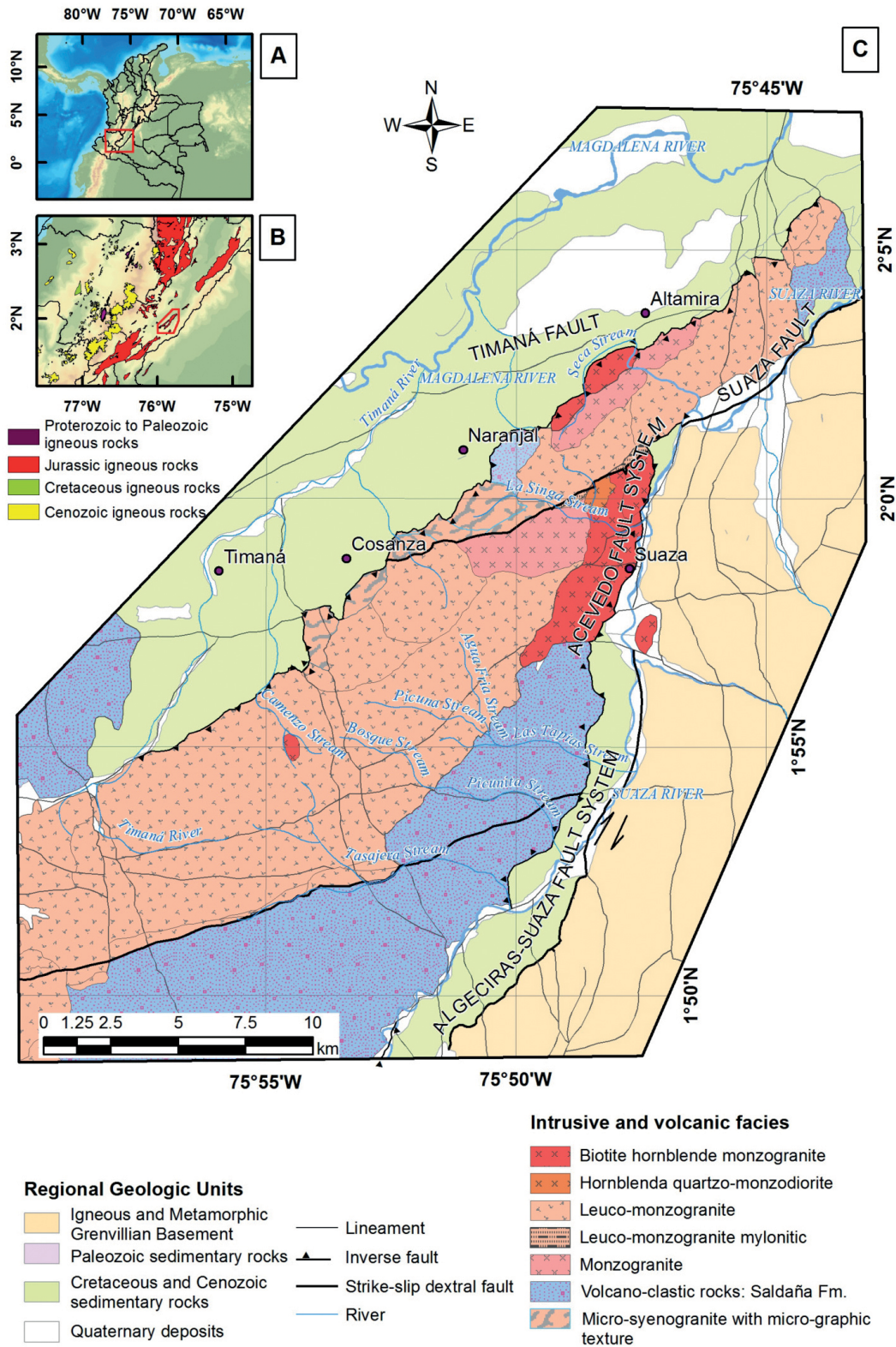
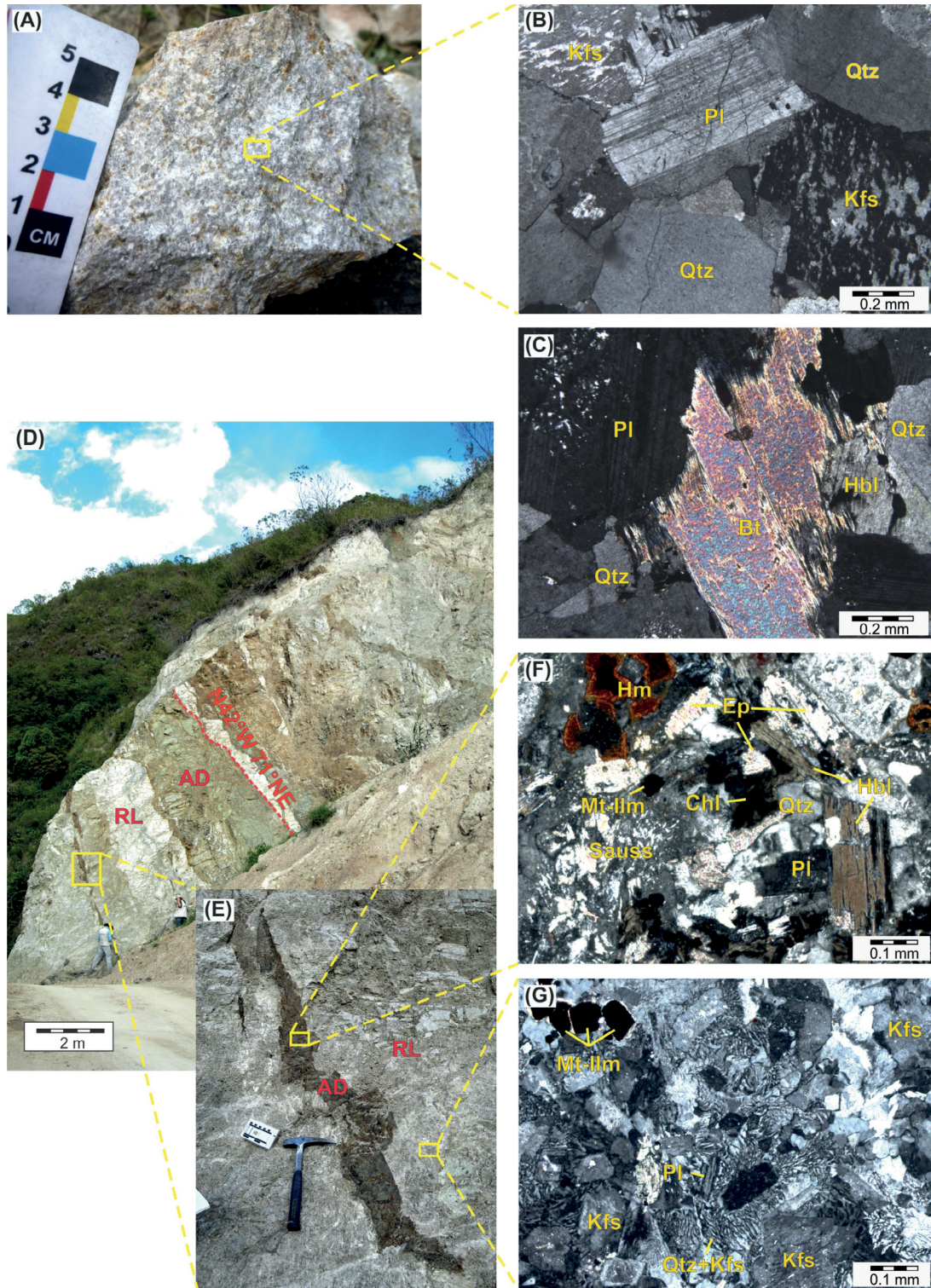


Figure 5. (A) Northwest South America, Central America and Caribbean showing Colombia and its internal departmental divisions. (B) Detail of the southern part of the Colombian Andes with the locations of the igneous rocks discriminated as Jurassic (red) with Proterozoic to Paleozoic (purple), Cretaceous (green), and Cenozoic (yellow) intrusive rocks. (C) Petrographic facies map of the Altamira Plutonic Massif.



Hb: hornblende; Qtz: quartz; Bt: Biotite; Pl: plagioclase; Kfs: alkali feldspar; Ser: sericite; Ep: epidote; Mag: magnetite; Hm: hematite; Ilm: ilmenite; Sauss: saussurite; Chl: chlorite.

Figure 6. Some geological and petrographic aspects of the Altamira Plutonic Massif. (A) Leucomonzogranite to syenogranite facies association, (B) typical textural aspect of the felsic minerals in this facies under cross polarized light, (C) biotite hornblende monzogranite facies association under cross and plane polarized light, respectively, (D) rhyolite (RL) and (E) andesitic dike facies (AD), (F) Intergranular texture in andesite rocks, under cross polarized light, and (G) micrographic intergrowths of quartz and alkali feldspar in rhyolite.

Mafic-intermediate dikes

Andesite and/or microdiorite dikes, often associated with porphyritic rhyolites (Figures 6D, 6E), are characterized by slightly planar flow structures and a very fine-grained, intergranular, texture, given by amphibole crystals filling in interstices left by plagioclase laths. Plagioclase grains are euhedral and are often replaced by chlorite and/or epidote, carbonate and quartz aggregates. Opaque minerals are altered to Fe-oxides (Figure 6F). Massive andesite dikes (20-40 cm thick) trending N55-65°E cut across monzogranites and hornblende granodiorites (Figures 6D, 6E). They are porphyritic, with plagioclase phenocrysts (usually zoned) from 0.5 to 1 mm surrounded by small grains (0.2 to 0.5 mm) of alkali feldspar, sometimes resembling anti-rapakivi textures. Amphibole phenocrysts are occasional and biotite phenocrysts are rare. The rock mesostasis has a microcrystalline texture and is made up of quartz-feldspar aggregates, with some opaque minerals and epidote. Fe-Ti oxides, apatite and zircon are common primary accessory minerals. Some thin-section areas and fractures are filled with quartz and alkali feldspar aggregates associated with fine-grained biotite (< 0.2 mm), epidote and titanite formed during late hydrothermal processes.

Rhyolite porphyry dikes

These rocks were mapped in the western areas of the massif. They are strongly fractured and weathered, with abundant clay development. They are closely related and oriented according to the same mafic-intermediate dike swarm trends. They are hololeucocratic ($CI \leq 5$) and contain plagioclase, quartz and minor proportions of alkali feldspar phenocrysts surrounded by a matrix of quartz-alkali feldspar micrographic intergrowths and very fine-grained chlorite, biotite and sericite aggregates (Figure 6G). Plagioclase phenocrysts are oligoclase and are generally substituted by white mica aggregates. Quartz phenocrysts are clean and rounded and usually have skeletal textures; they sometimes form aggregates in a glomeroporphyritic texture. Alkali feldspar phenocrysts are scarce. Amphibole, titanite and opaque minerals are the most common mafic minerals.

DISCUSSION

Geologic mapping of plutonic rocks should be done *a priori*, on the basis of descriptive, factual and easily observable or measurable rock properties defined in field outcrops and hand samples. Stratigraphic names should be applied with caution, avoiding nomenclatural ambiguities. We show that the granites and associated rocks that build the main intrusions in the Algeciras and Altamira Plutonic Massifs

may be mapped through descriptive criteria, using concepts as petrographic facies or facies associations (Ulbrich et al., 2001; Vlach, 1985, 1993) on a 1:50,000 scale. These mapping units are preliminarily assigned, given its distribution and extent, into large igneous structures named plutonic massifs, which could eventually be grouped into a larger Eastern Cordillera Batholith following, among others, the suggestions of Cobbing et al. (1981), as applied in the Peruvian Andes area. Notably, additional work is still needed to assign our mapped units into individualized structurally coherent igneous intrusions or plutons, as such intrusive units generally have $\leq 80-120 \text{ km}^2$ of exposed area (*e.g.*, Cobbing et al., 1981; Cobbing and Pitcher, 1972; Cobbing, 2000).

Distribution and petrographic variations

Contrasting petrographic facies or facies associations make up the Algeciras and Altamira Plutonic Massifs. In general, albeit for similar structures, textures and even mineralogical contents, they may be differentiated on the basis of mafic mineral contents and relative mineral proportions, whose differences could be properly mapped on scales of 1:50,000 or larger. The extension, distribution (*e.g.*, compositional variations) and structural (*e.g.*, the mylonitic foliation by deformation and dike orientation) relationships among the mapped units are significant, and certainly register the structural behavior and evolutionary history of each massif and thus the whole granite magmatism in the Colombian Eastern Cordillera.

As shown, mafic to intermediate rocks such as hornblende granodiorites, monzodiorites, and biotite hornblende monzogranites are more abundant in Algeciras than in the Altamira Plutonic Massif, the latter being made up largely of biotite-bearing leucogranites. Importantly, the Algeciras Massif has a slightly zoned pattern, to be further detailed, as evidenced near the Las Ceibas River area, where rocks vary from coarse-grained hornblende monzogranite to medium/fine-grained biotite hornblende monzogranite, and biotite monzogranite toward the western external contacts.

The exposed areas of the Algeciras and Altamira Plutonic Massifs are also different (ca. 500 vs. 280 km^2 , respectively). Of note, the exposed areas of the volcano-sedimentary rocks from the Saldaña Formation and the crystalline basement are larger and smaller, respectively, in the southern area neighboring the Altamira Massif. These geologic observations suggest a relatively higher uplift and erosion rates in the northern area, exposing relatively deep crustal units.

Bustamante et al. (2010) and Rodríguez et al. (2018) indicate that the mapped granites have geochemical affinities with rocks from continental magmatic arcs, typical of active plate margins. This hypothesis agrees with the high-K calc-alkaline trend depicted by our modal data (Figure 3), which in general is associated with a geodynamic subduction setting

in a continental margin (*cf.* Lameyre and Bowden, 1982; Nédélec and Bouchez, 2015). In this sense, as first working hypotheses, the felsic facies associations may contain relatively higher contributions from evolved crustal sources or may be generated by significant crystal fractionation processes from less evolved precursor magmas, or both. In addition, our geological (*e.g.*, syn-plutonic mafic-intermediate dikes, mafic microgranular enclaves) and textural (*e.g.*, plagioclase corrosion and reabsorption) evidence points to mingling and mixing processes involving basic-intermediate magmas (*e.g.*, Barbarin, 1990; Vernon, 2004), implying source contributions from the lithospheric mantle as well.

The associated subvolcanic rocks and the micrographic textures

The close association between the mapped plutonic rocks and the slightly younger or even coeval subvolcanic rocks and the fact that they intrude volcano-sedimentary sequences indicate they were emplaced at relatively shallow crustal level, a finding supported by the occurrence of micrographic intergrowths in some Algeciras leucogranites. However, specific studies to obtain intensive crystallization parameters are required.

Of importance, the observed quartz and alkali feldspar micrographic intergrowths and the spherulitic textures in porphyries suggest fast undercooling of the precursor silicic melts (*e.g.*, Fenn, 1986). Experimental data and natural examples show that this kind of intergrowth may result from the kinetics of crystal growth and elemental diffusion rates rather than representing a simple eutectic or cotectic crystallization (Fenn, 1986; Lentz and Fowler, 1992). For instance, in hydrous granitic compositions, *liquidus* undercooling about 75°C is enough to induce the development of micrographic textures (London, 1999), while skeletal quartz phenocrysts, as the ones described, may be experimentally produced from melts undercooled over 55°C in less than 24 h (*ca.* 2°C/h, *cf.* Swanson and Fenn, 1986). These remarks open way for additional research to determine whether such undercooling-related textures in the rhyolite porphyries from the Algeciras and Altamira Massifs are actually related to fast uplift ratios.

Deformation, mylonitization, and strain structures

The main mylonitic foliation patterns of the Algeciras and Altamira Massifs (Figures 4F, 4G), fracture (Figure 4I), and dike orientations (Figures 4I, 4L, 6D, 6E) conform well with the right lateral strike-slip orientation of the Algeciras Fault System, which affected Jurassic intrusive and volcanic rocks, as well as the supracrustal sediments (Velandia et al., 2005). This fault system might be active since the Early Jurassic and is inferred to be a main suture zone related to a main

compressive regime in a continental arc environment (*e.g.*, Rodríguez et al., 2018), which controlled the emplacement of the Algeciras and Altamira massifs. The penetrative foliation, specially develop in the massifs borders, with a NE-trending orientation of the mafic minerals, rotated feldspar crystals (Figures 4F, 4G) and/or quartz porphyroclasts in the most deformed varieties, suggest that strain was active from the syn- to the post-magmatic crystallization stages of the main magmatism.

The observed orientation systems of the mafic-intermediate and felsic dikes were also controlled by this NW-SE main strain pattern. However, they do not present solid-state deformation evidences. NE-trending dikes are sub parallel to the Algeciras Fault System, while others present NW trend, more or less orthogonal to the system. Thus, they may correspond to synthetic and antithetic structures, respectively, related to the right lateral strike-slip movement of the main fault system. In fact, some authors have suggested that the prevailing tectonic regime during the Jurassic was similar to that observed currently, with a transpressional fault system being related to the oblique (to orthogonal) convergence of a proto-Pacific plate behind the Andean block (Blanco-Quintero et al., 2014; Bustamante et al., 2016; Trenkamp et al., 2002; Velandia et al., 2005).

CONCLUSIONS

The herein named Algeciras and Altamira Plutonic Massifs are made up of several plutonic and subvolcanic petrographic facies or facies associations that could be routinely mapped. In addition to some textural and structural properties (*e.g.*, mineral zoning, intergrowth, foliation, alteration, recrystallization, etc.), the recognized rock varieties were differentiated mainly by their mafic mineral contents and mineral modal proportions, which are easily contrasted in field outcrops and hand samples. Up to eight plutonic and three subvolcanic facies or facies associations were recognized in the Algeciras Plutonic Massif, hornblende granodiorites, monzodiorites and biotite hornblende monzogranites being the most abundant rock types. Other five facies or facies associations were mapped in the Altamira Plutonic Massif, which is constituted mainly by a variety of leuco monzogranites.

Our data suggest a zoned facies distribution pattern in the case of the Algeciras Plutonic Massif, best evidenced along the Las Ceibas River and neighboring areas. The northern areas in this massif, with coarse-grained textures and relatively high hornblende contents, were perhaps formed under relatively higher temperature and pressure as compared to the west central and the northwest areas with medium- to fine-grained biotite monzogranites with no hornblende. Geologic and petrographic evidence suggest that the

intrusions were emplaced at relatively shallow crustal levels. Fast undercooling in subvolcanic varieties, as deduced from textures observed in felsic porphyries, may additionally indicate fast uplift ratios.

The main SSW-NNE elongation trend drawn by massif exposures, mylonite varieties and mapped fault/fracture systems suggest a syn- to post-magmatic transpressional field strain, arguably operating in response to a large-scale convergence during the Jurassic.

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