OCURRENCE OF GRANULITES IN THE NORTHERN PART OF THE WESTERN CORDILLERA OF COLOMBIA

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ABSTRACT

The following paper introduces a new unit composed of high-grade metamorphic rocks in the northern part of the Colombian Andes: the Pantanillo Granulite. The unit is exposed near Santa Fe de Antioquia (Antioquia Province), where the Cauca River Valley divides the Western and Central Cordilleras. The granulites are exposed in the western side of the Cauca-Almaguer Fault, which is the westernmost fault of the Cauca-Romeral system. This fault represents the main boundary between continental and oceanic lithospheres in the Colombian Andes.

The chief mineral parageneses determined in these rocks are Pl + Amp (hbl?) + Ol + Opx + Spl (hercynite) + opaques, Pl + Cpx + Opx, and Pl + Qtz + Opx + Cpx. These mineral associations are indicative of high-grade, granulite-facies conditions at relatively low P. The chemical composition of Pantanillo Granulite ranges between high-Mg tholeiitic basalt and komatiitic basalt. Trace-element diagrams are flat, similar to N-MORB, but somewhat depleted, a feature indicative of a plutonic protolith, although a volcanic one cannot be precluded. Tectonic discrimination diagrams based on trace elements suggest the granulite's protolith may have been formed in a tholeiitic arc. Whole-rock 40Ar/39Ar dating of the Pantanillo Granulite yielded 216.2 ± 14.2 Ma and K/Ar dating of amphibole yielded 360.7 ± 12.4 Ma. However, the very low content of potassium in these samples renders the ages practically useless. The possibility of excess argon in the samples is quite probable, so the geological meaning of the datings is uncertain at the moment

Keywords: granulite, Pantanillo, komatiitic basalt, Western Cordillera

OCURRENCIA DE GRANULITAS EN EL SECTOR SEPTENTRIONAL DE LA CORDILLERA OCCIDENTAL DE COLOMBIA

RESUMEN

El siguiente artículo presenta una nueva unidad compuesta por rocas metamórficas de alto grado localizada en la parte norte de los Andes colombianos: la Granulita de Pantanillo. Esta unidad está expuesta cerca de Santa Fé de Antioquia (Departamento de Antioquia), donde el valle del río Cauca divide las cordilleras Occidental y Central. Las granulitas son expuestas en el lado occidental de la falla Cauca-Almaguer, que es la falla más occidental del sistema Cauca-Romeral. Esta falla representa el límite principal entre litosferas continental y oceánica en los Andes colombianos.

Las principales paragénesis minerales determinadas en estas rocas son Pl + Amp (Hbl?) + Ol + Opx +Spl (hercinite) + opacos, Pl + Cpx + Opx, y Pl + Qtz + Opx + Cpx. Estas asociaciones minerales son indicativas de alto grado, condiciones de la facies granulita y relativamente baja P. La composición química de la Granulita de Pantanillo varía entre basaltos toleíticos de alto Mg y basalto komatiiticos. Los diagramas de elementos traza son planos, similares al N-MORB, pero más empobrecidos, un rasgo indicativo de un protolito plutónico, aunque el protolito volcánico no puede descartarse. Diagramas de discriminación tectónica basados en elementos traza sugieren que el protolito de las granulitas pudo haber sido formado en un arco toleítico. Una datación 40Ar/39Ar en roca total de la Ganulita de Pantanillo arrojó una edad de 216,2 ± 14,2 Ma y una datación K/Ar en anfíbol dio una edad de 360,7 ± 12,4 Ma. Sin embargo, el bajo contenido de potasio en las muestras hace que las edades no sean confiables. La posibilidad de exceso de argón en las muestras es bastante probable, por lo que el significado geológico de las dataciones es incierto en el momento.

Palabras clave: Granulita, Pantanillo, basalto komatiitico, Cordillera Occidental.

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INTRODUCTION

During the previous decade, INGEOMINAS (Colombian National Institute for Geology and Mining – current Servicio Geológico Colombiano) compiled and produced new geologic, structural, and geochemical information of the northern portion of western Colombia, focusing on the area where the NS-trending faults of the Cauca-Romeral system are exposed. During the course of the work, some contradictions were established as regards the lithostratigraphic character, origin, and structural positions of some of the geologic units. Of particular interest was the location of units respect to the Cauca-Almaguer Fault, which many authors deem to be the chief boundary between continental and oceanic lithospheres in the Colombian Andes (e.g. Maya y González, 1995). This major tectonic boundary is therefore regarded to represent the Mesozoic plate margin onto which oceanic tectonostratigraphic terranes of Western Colombia were accreted.

The Pantanillo Granulite crops out west of the Cauca-Almaguer Fault near Santa Fe de Antioquia. Previous authors had mapped the granulites as amphibolites (e.g., McCourt, 1984, Aspen *et al*., 1987, Maya y González, 1995; Nivia y Gómez, 2005; Álvarez y González, 1978). The recognition that these rocks actually contain granulite-facies assemblages was initially published in the report by GEOESTUDIOS-INGEOMINAS (2005). Important questions arised from this novel discovery: (a) what is the significance of granulite-facies conditions at the boundary between oceanic and continental affinity rocks in Colombia? (b) What is the spatial relation between granulites and rocks of the adjacent Sabanalarga Batholith? These two questions are addressed in the following contribution, which presents new petrographic, geochemical, and geochronologic data on the origin and evolution of the Pantanillo Granulite, and the implications of their discovery on the tectonometamorphic evolution of northwestern Colombia.

GEOLOGIC SETTING

The studied area is located in the central part of the Province of Antioquia, between the western flank of the mostly continental Central Cordillera and the eastern flank of the chiefly oceanic Western Cordillera. Geologic mapping in this broad area has allowed identifying some fault-bounded geologic units (e.g., Toussaint, 1976; Aspen *et al*., 1987, Alvarez y González, 1978; González *et al*., 2001). Blocks that are relevant to this study include the Cretaceous tholeiitic basalts of the Barroso Formation, which are exposed along the margin of the Western Cordillera, and intermediate granitoids of Mesozoic age such as the Sabanalarga Batholith (Álvarez y González, 1978) and the Buriticá Tonalite (González y Londoño, 2002). It is in this kind of granitoids that lens-shaped bodies of metamorphic rocks as the Pantanillo Granulite occurs (Álvarez y González, 1978; GEOESTUDIOS-INGEOMINAS, 2005). In contrast, the fringe of the Central Cordillera is characterized by metamorphic rocks of the Arquía and Cajamarca complexes, separated by the fault-bounded Cretaceous Quebradagrande Complex, an association of oceanic sedimentary and volcanic rocks metamorphosed to low-grade conditions (FIGURE 1).

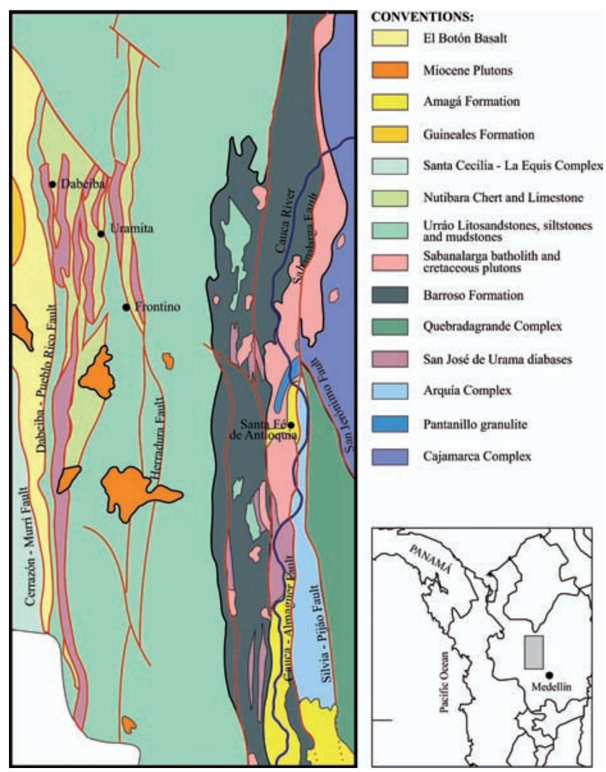

FIGURE 1. Simplified geologic map of the northern portion of the Central Cordillera and the Western Cordillera of the Colombian Andes.

The boundaries between tectonic blocks are the faults of the Cauca-Almaguer system (Maya y González, 1995). This system is composed of a complex array of NS-trending regional faults and shear zones. Within the system, the Cauca-Almaguer Fault is interpreted to represent the Early Cretaceous suture between continental basement to the east and oceanic lithosphere to the west (McCourt *et al*., 1984). In between faults, imbrication of slivers of various structural levels renders the recognition and differentiation of rock units very challenging.

The other instances of high-grade, granulite-facies metamorphic rocks so far recognized in the northwestern Andes of Colombia are exclusively in the Central Cordillera, east of the Cauca-Romeral system. Examples include the El Retiro granulite (Restrepo y Toussaint, 1984; Ardila, 1986; Correa y Martens, 2000; Rodríguez *et al*., 2005, 2008), Puquí Complex (González, 1993), and San Isidro (Rodríguez y Albarracín, in press). Interestingly, the Pantanillo occurrence is located on the Cauca-Almaguer Fault, within the oceanic domain of the Colombian Andes, and spatially associated with the Sabanalarga Batholith.

K/Ar dating in hornblende and biotite of the Sabanalarga Batholith east of the Cauca-Almaguer Fault yielded 98 ± 3.5 Ma and 97 ± 10 (González *et al*., 1976; González y Londoño, 2002). The Buriticá Tonalite, a pluton west of the above-mentioned fault and potential correlative of the Sabanalarga, yielded analogous ages (Göbel and Stibane, 1979; González y Londoño, 2002). Another possibly correlatable pluton, the Altamira Gabbro, yielded a 77.4±7.7 Ma and 92.5 ± 4.2 Ma K/Ar (plagioclase) ages (Restrepo y Toussaint, 1976; Toussaint y Restrepo, 1978). The similar geochemical character of the above granitoids, their spatial association, and their petrographic similarities suggest that these plutons may be genetically related.

If the 95 Ma age for the Sabanalarga Batholith is confirmed, it would suggest that the metamorphic continental basement and the oceanic rocks of the Barroso Formation had been amalgamated previous to this time. Furthermore, the Sabanalarga would have been emplaced along the Cauca-Almaguer discontinuity. An alternative idea is that at the time of intrusion, the fault that separated the oceanic and continental domains was located further to the west.

Some authors have proposed that the Sabanalarga Batholith is in actuality two different rock bodies separated by the Cauca-Almaguer fault (Nivia y Gómez, 2005; Flórez y Valencia, 2006; Weber *et al*., 2011). According to this idea, the two plutons were crystallized contemporaneous, but in disparate tectonic positions to be juxtaposed later by faulting.

METHODS

Twenty-three thin sections were studied and classified based on the recommendations of the Subcomission on the Systematics of Metamorphic Rocks (Fettes and Desmons, 2007). An exception is the use of the term "mafic granulite", which will be used here to denote high-grade, granulite-facies metamorphic rocks dominated by Fe-Mg silicates. Similarly, structural, textural, and microstructural terms used in the text follow Agustithis (1990), Winter (2001), and Vernon (2004). Mineral abbreviations are those of the SCMR (Fettes and Desmons, 2007).

Chemical analyses were conducted at Actlabs, Canada, and they included analyses of five samples from the Cauca-Romeral project, 11 from the Western Cordillera project, both of INGEOMINAS, and three from the thesis by Cardona (2010). Concentrations of major oxides, trace elements, and rare-earth elements were determined by inductively-coupled-plasma mass spectrometry.

Geochronology was conducted on two samples of the mafic granulite at Actlabs, Canada. Step-heating 40Ar/39Ar geochronology was performed on the bulk of sample IGM-706332 and K/Ar dating was performed on amphibole extracted from sample JJ0003. Additionally, mineralogical determinations of the latter sample were performed by energy-dispersive spectroscopy (EDS) at Queens University, Canada.

FIELD CHARACTERISTICS

The Pantanillo Granulite was originally mapped as an amphibolite unit associated with the Sabanalarga Batholith (sheet I-7 Urrao by Álvarez y González, 1978; sheet 130 - Santa Fe de Antioquia by Mejía, 1984). The report by GEOESTUDIOS-INGEOMINAS (2005) describes the granulite as an NE-SW-elongated unit that crops out in a 12,7 km2 area that extends from the town of Liborina to the upper part of La Sapera Creek, ca. 5 km NW of Santa Fe de Antioquia (FIGURE 2). The unit crops out as a series of banded granulites and amphibolites, the bands thickness ranges from a few centimeters to ca. 1 m. Individual bands can be recognized by their distinct mineral composition, grain size, texture, and color. The boundaries between bands can be sharp or transitional. In field discussions some geologists have suggested that the banding may be a relict primary feature produced by igneous mineral settling (Cardona, J., 2010). However, there are cm-scale planar structures that crosscut the schistosity, perhaps mafic dikes. Interestingly, inside these bands, amphibole crystals are parallel to the dominant foliation of the rock, at an angle with the direction of the possibly dike, indicating that the banding is metamorphic origin. Also, isoclinals folding of the bands parallel to the schistosity can be observed rarely, indicating that the schistosity is a metamorphic feature (FIGURE 3C).

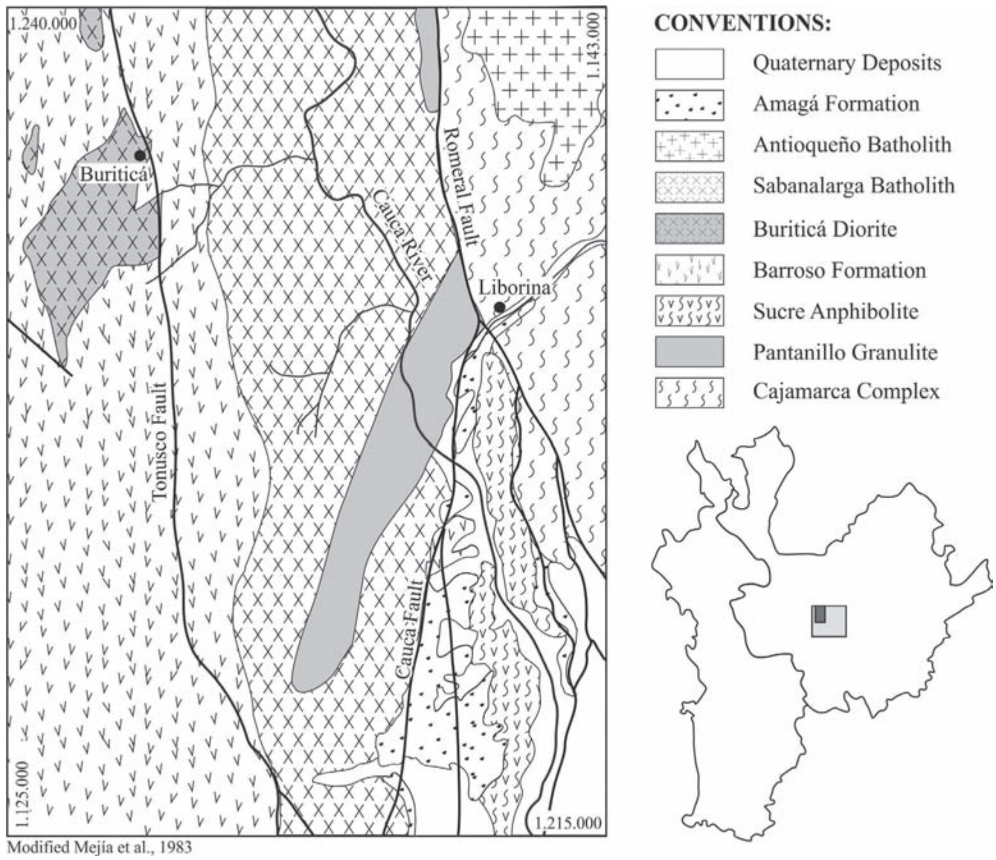

FIGURE 2. Detailed geologic map of rock units around the Pantanillo Granulite

Most rocks are medium to fine grained, the microstructure is either granoblastic, or foliated, with or without preferentially-oriented minerals, and their color is gray-green with mottled white spots or dark gray to white mottled with dark-green zones. Outcrop scale structures include decimetric to metric scale folds. Some of the granulites show banded and stromatic migmatitic structure (FIGURE 3). However, most samples show a good schistosity imparted by the orientation of the amphibole.

The granulite unit is cut by pegmatite dikes composed of large crystals of plagioclase and ferromagnesian mineral (pyroxene?), by tonalite-quartzdiorite dikes with low hornblende content (<5%), and by basaltic dikes. In thin section, the granulites shows typical nematoblastic textures produced by preferentially-oriented amphibole. The characteristic mineral orientation is subdued or absent near the contact with the igneous rocks of the Sabanalarga Batholith. Local outcrops show igneous injections parallel to the schistosity planes producing injection migmatites with *lit par lit* structures, showing clearly the intrusive nature of the Sabanalarga Batholith in the Pantanillo Granulite.

Contrasting opinions exist in regard to the contact between the Sabanalarga Batholith and the Pantanillo Granulite. Mejía (1984) and Cardona (2010) report that the tonalite intrudes the granulite; GEOESTUDIOS-INGEOMINAS (2005) described the contact as transitional. Locally the contact is faulted. Close to the contact, the Sabanalarga Batholith shows migmatitic injection structures which obscure the contact. The pluton is composed of two chief facies: hornblende gabbros and diorites cross cut by a quartzdiorite-tonalite facies. Dikes with a range of compositions intrude the pluton. The area is also crossed by N to NE-trending faults that cut the granulites and the plutons, some of them forming mylonite zones of several meters. The foliation of the granulites is relatively constant throughout the region, with strikes ranging N45–76E .

PETROGRAPHIC DESCRIPTIONS

By re-examining available thin sections collected in previous projects by INGEOMINAS (TABLE 1), we were able to trace additional outcrops of granulites and amphibolites at Rodas Creek (samples IGM-95627 and IGM- 95628), north of the main unit, on the eastern side of the Cauca River and within the igneous body. The chief conclusion that we draw from re-examining the thin sections is that granulites occur on both sides of the Cauca-Almaguer fault.

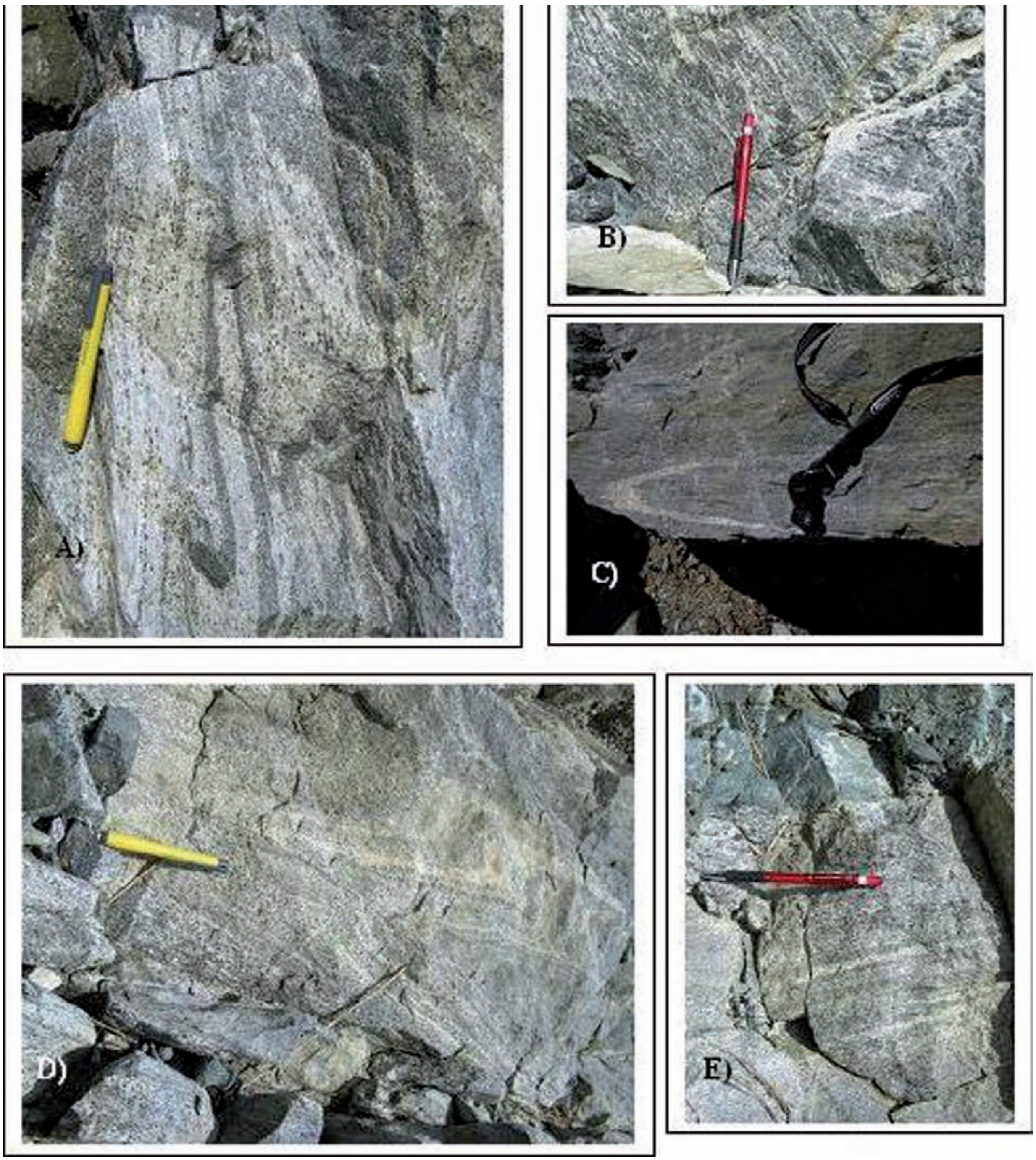

FIGURE 3. Outcrop photographs of Pantanillo Granulite exposing banded and folded structures in both granulites and amphibolites. **A**) and **D**) Migmatites with folded structure and compositional layering. **B**) Medium grained rock with a poorly developed schistosity. **C**) Very tight isoclinals folding of the bands parallel to the schistosity. **E**) Migmatitic rocks with banded structure.

The mineral paragenesis of granulites include:

- Plagioclase + amphibole (hornblende) + olivine + orthopyroxene + spinel (hercynite) + opaques
- Plagioclase + clinopyroxene + orthopyroxene + retrograde amphibole
- Plagioclase + quartz + orhtopyroxene + retrograde amphibole

Amphibolites:

- Plagioclase + clinopyroxene + retrograde amphibole
- Plagioclase + amphibole (hornblende)

TABLE 1. Modal mineralogic compositions of Pantanillo Granulite rocks.

IGM	Qtz	Pl	Fsp	Ol	Cpx	Opx	Anf	Hbl	Tr/Act	Bt	Chl	Op	Ap	Zr	Spl	Rt	NOMBRE DE LA ROCA
GRANULITES																	
706332		27		3		4,3	62								4		MAFIC GRANULITE
706334		15		3		4,7	70					TR			7		MAFIC GRANULITE
706337		41			0,1	0,1		59				TR	TR				MAFIC GRANULITE
706338	2	47			13	29		8,4				2	TR			TR	GRANULIT OF Pl, Opx, Cpx, Hbl
706340		28		1		11	57						TR		3		MAFIC GRANULITE
706343	18	64			14	5,5	4,9					3	TR				GRANULIT OF Pl, Qtz, Cpx, Opx
706345		51			31	13	2,7					3					MAFIC GRANULITE
706346		31			3,4	1,4		60	1,4			3					MAFIC GRANULITE
JM043R	1	69			2	**9.4**		8,9			1	8					MAFIC GRANULITE
JM085R	5	50			9	15		20				1					MAFIC GRANULITE
VR203R	4	50			10	9,8		2,8	20		1	1	Tr				MAFIC GRANULITE
VR222R		18		2		17		56			X	Tr			7		MAFIC GRANULITE
VR197R	9	26	4		12	6		42	Tr	2	Tr	0		Tr			GRANULIT OF Pl-Hbl-Cpx-Qz con Opx
95641	11.2	67.1			3.3	1.9		13.4				0.6	0.2				GRANULIT OF Pl, Hbl con Opx y Cpx
95642		28			25	11		37									MAFIC GRANULITE
95626		40			7	4	40					1			8		MAFIC GRANULITE
95627		51.6			5.4	TR		43				TR	TR				MAFIC GRANULITE
95628		70.4						29.6				TR					AMPHIBOLITE
ANPHIBOLITES																	
706331	X	45						55		0	X	1					AMPHIBOLITE
706333		61					36										AMPHIBOLITE
706335		9					76					TR			TR		AMPHIBOLITE
706336		22			36			36				7			TR		ROCK CALCOSILICATADA
6844		39						60									AMPHIBOLITE

Based on the mineral assemblages, granulites can be divided into three groups: mafic granulites with orthopyroxene, olivine, amphibole (hornblende) and hercynite; mafic granulites with two pyroxenes; and quartz-bearing granulites with two pyroxenes. Most olivine-bearing granulites are fine grained and their orthopyroxene is not retrograded. In the granulites with two pyroxenes and the cpx-bearing amphibolites, pyroxenes are partially replaced by amphibole. Quartz-bearing granulites are limited to the felsic bands and they contain flaser quartz. Similarly, amphibolites can be divided into those containing hornblende+plagioclase and those containing pale amphibole+plagioclase. Finally, subordinate mafic granofels with clinopyroxene, plagioclase and retrograde amphibole was observed.

In addition to granulites, the Pantanillo unit contains amphibolites and mafic granofels. Amphibolites can be divided into those composed of hornblende and plagioclase, and those composed of pale amphibole and plagioclase. Mafic granofelses contain clinopyroxene, plagioclase, and retrograde amphibole.

Plagioclase in the granulites has compositions between labradorite and anorthite; measurements by optical method means yielded An52-An71, which possibly are underestimations taking into account that the EDS spectra of plagioclase from one sample is nearly pure anorthite (FIGURE 4A). Plagioclase is xenoblastic, crystals are 0.1-0.4 mm, and the mineral constitutes between 15% and 65% of the bulk rock. Plagioclase is either oriented parallel to the rock's dominant foliation or it shows granoblastic texture with polygonal triple contacts. Crystals are either untwinned or show diffuse or wedged albite twin. Some plagioclase crystals contain equant inclusions of spinel or amphibole; some plagioclase is also part of symplectite with spinel.

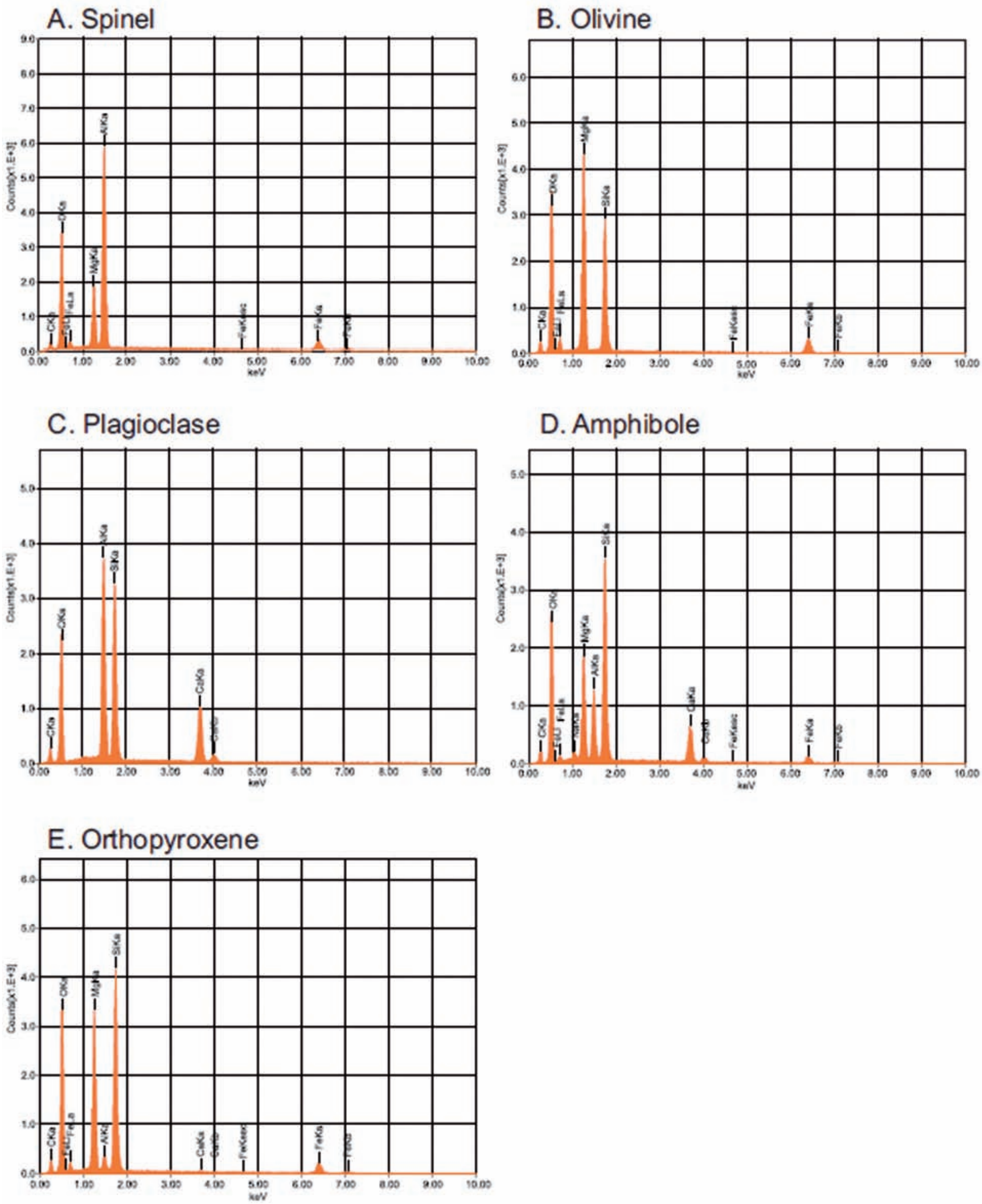

FIGURE 4. EDS spectra of minerals in mafic granulite sample JJ0003.

Pale amphibole is present in the olivine-bearing granulites and in some of the amphibolites. The mineral constitutes 55-70% of these rocks. EDS analysis confirmed the amphibole is magnesium-rich hornblende (FIGURE 4B). The amphibole is in contact with plagioclase, olivine, and orthopyroxene. Amphibole crystals are xenoblastic to idioblastic, and grain size ranges 0.2–1 mm. The color of the amphibole is pale green, pleochroic, and birrefrigence is up to first-order red. The measured extinction angles range 14–29°. The amphibole defines a nematoblastic texture in some of the granulites. Amphibole crystals contain sub-equant inclusions of plagioclase, orthopyroxene, olivine, and spinel.

The presence of orthopyroxene was confirmed by EDS analysis (FIGURE 4C). Its crystals are smaller than amphibole, and they are contained both in the matrix and as inclusion in amphibole. Most orthopyroxene is present in restricted bands within the rock. In the granulites with clinopyroxene, the orthopyroxene may contain sub-equant inclusions of plagioclase, hornblende, clinopyroxene, opaque (ilmenite?), and needles of rutile along cleavage planes. Orthopyroxene crystals are xenoblastic and mineral outlines are lobulated or straight polygonal. The mineral shows week pleochroism with X=pale pink, Y=pale green-yellow, and Z=pale green. Some orthopyroxene crystals show hornblende corona. Orthopyroxene forms granoblastic mosaics with clinopyroxene and plagioclase, and it is slightly altered to smectite and talc.

Olivine is fayalite rich (FIGURE 4D) and it constitutes <5% of the bulk of the rocks. Its crystals are xenoblastic, lobulated, elongated, and they have a preferred orientation. Olivine occurs in bands along with spinel, pale amphibole, and plagioclase. Some crystals show alteration to iddingsite with opaques (magnetite?) forming inside fractures or within borders. Olivine occurs chiefly in the matrix along with pale amphibole and plagioclase, or as sub-equant inclusion in amphibole. Some grains show kelyphitic coronas at contacts with plagioclase, where spinel-bearing symplectites were developed (FIGURE 5).

The spinel is emerald green and its composition corresponds to a Mg spinel + hercynite solid solution (FIGURE 4E). This mineral is present in the olivine-bearing granulites where it forms <7% of the bulk of the volume. Spinel crystals are xenoblastic and their grain size ranges 0.03–0.25 mm. The mineral is chiefly contained in bands with groups of crystals exhibiting lobulated grain boundaries or as intersticial and intergranular grains. The hercynite is also present as part of symplectite aggregates along with plagioclase, or as kelyphitic coronas around olivine. Some hercynite contains equant incluions of plagioclase and olivine, and in turn, it is contained as inclusion in pale amphibole.

The clinopyroxene (diopside?) is present in the two-pyroxene granulites and in the amphibolites, and the mineral constitutes up to 30% of these rocks. The clinopyroxene is mostly xenoblastic to subidioblastic with lobulated grain boundaries, its extinction angle ranges 34-43°, and both simple and polysynthetic twins are present. The clinopyroxene crystals contain sub-equant inclusions of plagioclase, orthopyroxene, and opaque grains. Some of the studied samples showed retrogression coronas of hornblende or actinolite.

Hornblende crystals are primary amphibole and retrograde products chiefly from pyroxene. The primary amphibole is a major mineral both in amphibolites and in granulites poor in pyroxene. Hornblende occurs both as granoblastic aggregates with straight triple contacts or defining a nematoblastic texture. In case of retrogression, hornblende is formed from pyroxene, either as corona or within irregular patches along pyroxene cleavage planes.

When present, quartz is restricted to bands within the intermediate-composition granulites that are rich in plagioclase. Quartz crystals are larger than the other mineral phases in the rock, showing subrounded and lobulated grain boundaries. Quartz is usually elongated and oriented parallel to the compositional banding (flaser quartz), showing strong undulatory extinction. Accesory minerals in the granulites include opaque grains, apatite, and rutile.

Conditions of Metamorphism

Based on the finding of hypersthene and clinopyroxene, calcic plagioclase, and spinel, GEOESTUDIOS-INGEOMINAS (2005) proposed that the Pantanillo Granulite formed at high-temperature (ca. 700 °C) and low-pressure (<0.6 Gpa), conditions that correspond to granulite-facies. The presence of hornblende with relict cores of pyroxene suggests retrogression under high-amphibolite-facies conditions.

Additional petrographic examinations undertaken during this investigation confirmed the diagnostic association of two-pyroxenes devoid of quartz and garnet in mafic protoliths, which is representative of high-T, low-P conditions. The most common mineral parageneses in the granulites are Pl + Opx + Cpx ± Am, Pl + Am + Opx + Ol + Spl, and in the amphibolites Pl + Cpx + Am and Pl + Am. These parageneses coexist in adjacent compositional bands suggesting that the two-pyroxene granulite-facies conditions were reached for a wet system. This in turn suggests that the T of equilibration is within the 650-850 °C range (Bucher and Frey, 2002). The presence of primary amphibole and retrograde amphibole, in some cases >40%, suggests that the metamorphosed system was hydrated both in the prograde and the retrograde paths. The presence of hercynite and absence of garnet is diagnostic of low pressure (<0.4 GPa; Bucher and Frey, 2002). Following the terminology proposed by the SCMR, the olivine-bearing granulites were formed at pyroxene-hornfels P-T conditions, although in this case we interpret the rocks to have formed by regional metamorphism. The partial retrogression of pyroxene into hornblende and the growth of late hornblende in the matrix indicates drop in temperature from peak granulite-facies to amphibolite-facies conditions.

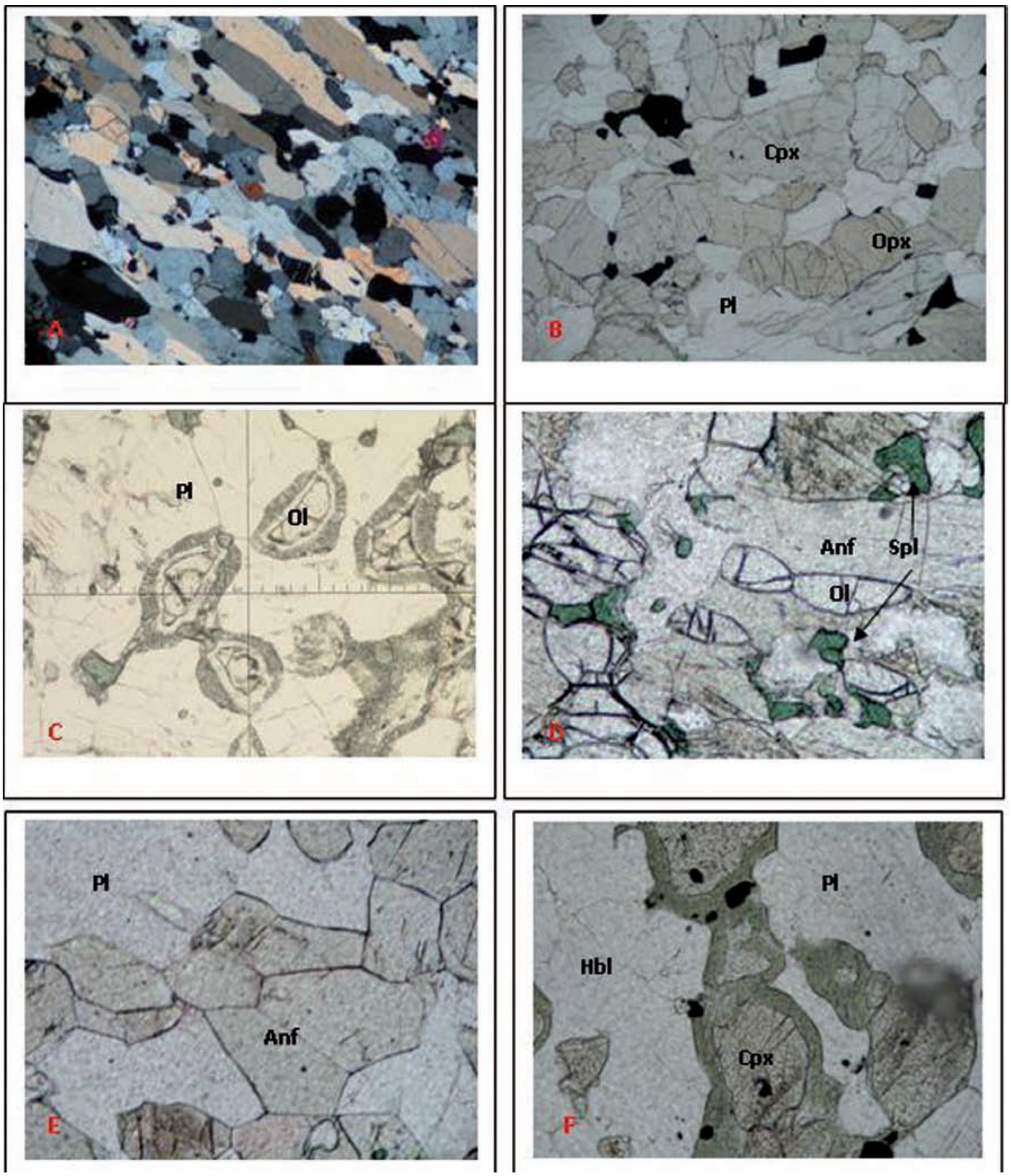

FIGURE 5. Textures and mineral compositions of Pantanillo Granulite. **A**) Nematoblastic texture; **B**) Granoblasltic texture of two-pyroxene granulite; **C**) Kelyphitic corona around olivine; **D**) Mafic granulite with olivine; **E**) Polygonal texture; F hornblende coronas around clinopyroxene.

GEOCHEMISTRY

In the following section, the geochemical characteristics of granulites are presented. We conclude that their protolith was igneous, possibly plutonic due to the absence of metasedimentary rocks, but a volcanic protolith cannot be totally precluded.

Major oxides

The result of major-oxide analyses is presented in TABLE 2. SiO2 content ranges between 43% and 58.5%, the higher value corresponding to quartz-bearing granulites. Interestingly, the chemical composition of granulites and amphibolites is very similar. It should be noted, however, that high-grade metamorphism under amphibolite- and granulite-facies conditions may have altered the original content of major elements, due to their mobility.

Most analysed granulite and amphibolite samples yielded TiO2 < 0.6%; only two samples yielded TiO2 ~ 1% (samples 706336 and JM043R). K2O content is low, mostly less than 0.12%, but in sample VR197R, which contains K-feldspar, K2O is 0.85%. CaO content is relatively high, ranging 8.7%-15.5%, and inversely correlated with SiO2. Most rocks contain Al2O3/TiO2 > 20, with the exception of one outlier sample where the ratio yielded 8.8; the high opaque content, which is probably the Ti-phase, explains this anomaly.

TABLE 2. Major oxides of Pantanillo Granulite samples.

Muestra	SiO2	Al2O3	Fe2O3	MnO	MgO	CaO	Na2O	K2O	TiO2	P2O5	LOI	SUM
706332	43	16,34	8,71	0,129	17,91	9,63	1,06	0,02	0,191	< 0.01	1,39	98,39
706333	47,9	20,36	4,73	0,081	9,92	13,74	1,28	0,04	0,173	0,03	1,74	99,99
706334	44,34	16,97	8,65	0,123	17,28	10,3	1,09	0,04	0,206	0,04	1,41	100,4
706336	44,02	9,56	16,83	0,19	9,99	15,48	0,9	0,11	1,089	0,09	0,37	98,62
706337	48,5	17,38	6,88	0,129	9,76	14,32	1,25	0,08	0,378	0,01	1,23	99,91
706338	50,29	16,44	10,36	0,182	8,23	11,87	1,4	0,03	0,27	0,03	0,15	99,25
706340	45,19	17,96	7,83	0,12	15,39	11,09	0,96	0,02	0,24	0,03	0,77	99,6
706343	58,59	17,15	8,53	0,131	3,19	9,64	0,94	0,01	0,318	0,06	0,28	98,85
706345	47,15	16,94	12,51	0,203	9,17	13,59	0,59	< 0.01	0,349	< 0.01	0,16	100,7
706345	46,15	16,72	12,46	0,203	9,12	13,37	0,57	< 0.01	0,342	0,01	0,23	99,2
706346	47,78	13,2	12,43	0,201	11,01	12,58	1,08	0,04	0,535	0,12	1,2	100,2
JD-003	43,8	17,82	8,6	0,118	17,29	10,39	0,79	0,03	0,096	< 0.01	1,32	100,2
JD-023A	45,3	18,63	10,11	0,172	7,18	13,94	1,08	0,09	0,643	0,2	1,07	98,41
JD-030	43,34	16,16	9,43	0,132	18,85	8,71	1,1	0,06	0,092	0,02	1,63	99,52
JM043R	45,69	20,52	13,41	0,22	4,3	12,26	1,97	0,07	1,02	0,58	0,1	99,85
JM085R1	57,7	13,92	9,3	0,23	6,71	9,8	1,45	0,12	0,33	0,03	0,4	100
VR197R	55,61	9,28	10,48	0,17	12,15	8,8	1,33	0,85	0,42	0,11	0,5	99,82
VR203R	50,9	15,02	10,61	0,19	9,64	11,48	1,31	0,04	0,22	0,03	0,4	99,89
VR222R	44,01	17,67	8,9	0,11	16,45	10,21	0,91	0,04	0,18	0,03	1,3	99,9

Most samples of the Pantanillo Granulite contain high MgO, which ranges between 8-19%. However, samples with high SiO2 (56-58%; samples 706343, JM043R and JM085R1) contain MgO<8%. The CaO and MgO content of the associated plutonic rocks (i.e., Sabanalarga Batholith) is notoriously lower: MgO<5% and CaO<10%. The plutonic rocks are also characterized by higher Na2O ranging 1.6-4.4%.

On the TAS diagram (Le Bas *et al*., 1986) for volcanic rocks, the analysed samples plot in the fields corresponding to picritic basalt, basalt, and andesite with subalkaline affinity. Some of the rocks have such high Mg-contents that they plot within the picrite and komatiite fields. Plotting the suite in the De la Roche *et al*. (1980) diagram for plutonic rocks (FIGURE 6) shows that most samples are in the ultramafic and gabbronorite fields, a result that is concordant with the petrographic determinations for the metamorphic equivalents (i.e., the granulites and amphibolites).

The diagram after Rickwood (1989; FIGURE 7) shows that Pantanillo Granulite can be subdivided into two major and one minor groups. Eight samples plot in the komatiitic basalt field, five in the Mg-rich tholeiitic basalt field, and five in the calcalcaline andesite field. The first group is composed of samples 706332, 706334, 706340, 706346, JD-003, JD-030, VR-197R, VR-222R. Most of these samples contain the Pl + Am + Opx + Ol + Spl paragenesis. Group two is composed of samples VR-203R, 706333, 706336, 706337, 706345, which correspond to the two-pyroxene granulites or amphibolites. The third and minor group corresponds to samples JM-043R, JM-085R1, 706338, 706343, JD-023a, which are the samples that contain quartz. These rocks are interpreted as leucosomatic bands within the Pantanillo unit.

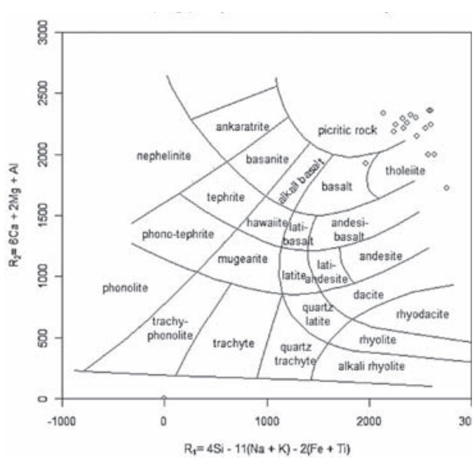

FIGURE 6. Chemical classification of Pantanillo Granulite. a) TAS diagram R1 and R2 for plutonic rocks (De la Roche *et al*., 1980).

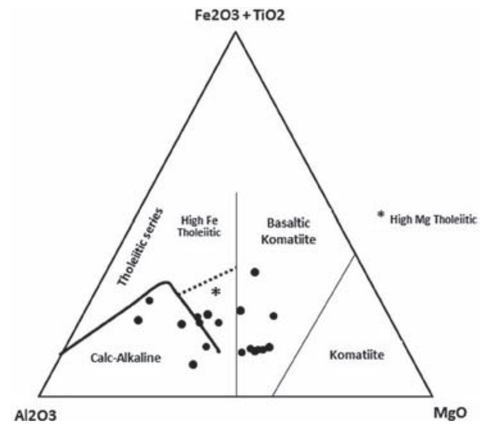

FIGURE 7. Classification diagram of Pantanillo Granulite based on their MgO, Al2O3, and FeO+Fe2O3+TiO2 (modified from Jensen, 1976, by Rickwood, 1989).

Trace Elements

TABLE 3 contains the results of REE and trace element analyses of 19 samples collected from the Pantanillo Granulite. Inasmuch as high-grade metamorphic rocks may be affected by mobilization of major elements, a handicap when using them for classifications, we present diagrams based on the relatively immobile trace elements. It should be noted that at granulite-facies conditions even those elements may have been mobilized.

The Th-Co diagram for volcanic rocks by Hastie *et al*. (2007) (FIGURE 8A) was envisioned to be insensitive to alterations by weathering, hydrothermal processes, and metamorphism. The diagram does not include a field for ultramafic rocks. Inasmuch as it is hard to tell whether the protolith of the granulites was a volcanic or a plutonic rock, the applicability of the Hastie *et al*. (2007) is uncertain.

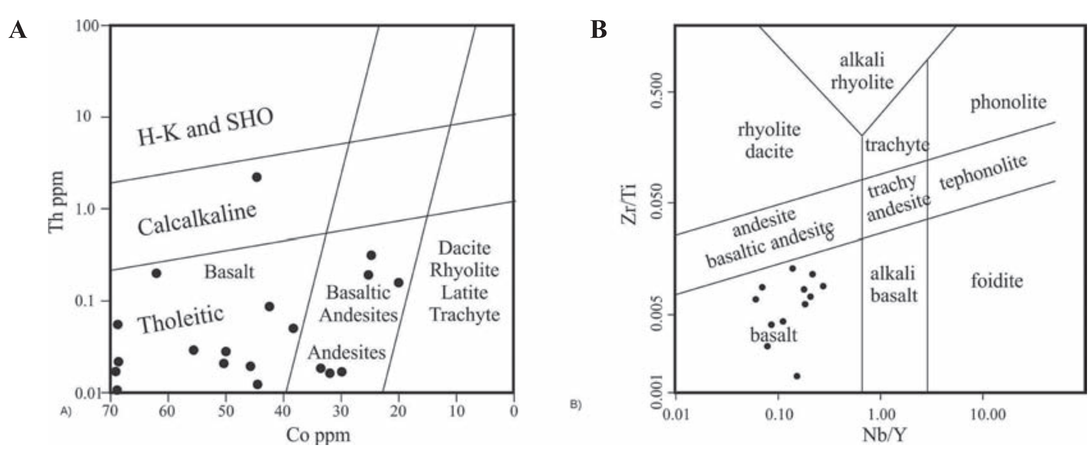

FIGURE 8. Rock classification diagrams used for Pantanillo Granulite compositions. **A**) Diagram after Hastie *et al*., 2007; **B**) Diagram after Winchester and Floyd, 1977 modified by Pearce (1996).

TABLE 3. Trace-element and rare-earth-element concentrations of Pantanillo Granulite

Muestra	Sc	Be	V	Cr_2O_3	Co	Ni	Cu	Zn	Ga		As	Rb	Sr	Y	Zr	Nb	Mo	Ag		Sn	Sb
706332	13	<1	66	190	69	520	<10	60	10	0,9	<5	<1	39	3,2	13	0,7	<2	<0,5	<0,1	<1	0,6
706333	22	<1	70	680	30	250	<10	<30	10	0,9	<5	<1	95	5,3	26	1,7	<2	<0,2	<0,1	<1	0,6
706334	12	<1	68	110	70	490	<10	50	10	1	<5	<1	46	3,6	11	1	<2	<0,5	<0,1	<1	0,7
706336	90	<1	738	110	51	50	120	80	13	1,7	<5	<1	177	7,7	17	0,6	<2	<0,5	<0,1	<1	0,3
706337	36	<1	169	1030	34	180	60	50	12	1,2	<5	<1	123	7,6	14	1,4	<2	<0,5	<0,1	<1	0,3
706338	46	<1	223	220	38	60	20	80	13	1,5	<5	<1	163	5	11	0,3	<2	<0,5	<1	<1	0,5
706340	15	<1	83	160	56	420	<10	40	10	0,8	<5	<1	128	3,9	12	0,7	<2	<0,5	<1	<1	0,8
706343	25	<1	187	<20	23	20	20	60	13	1,1	<5	<1	170	1,1	3	<0,2	<2	<0,5	<1	<1	<0,2
706345	54	<1	400	150	46	50	90	70	12	1,6	<5	<1	134	1,8	9	0,2	<2	<0,5	<1	<1	<0,2
706345	54	<1	395	150	46	50	100	70	12	1,6	<5	<1	129	1,8	3	<0,2	<2	<0,5	<1	<1	<0,2
706346	61	<1	401	420	50	80	120	80	12	1,9	<5	<1	115	9,2	13	0,8	<2	<0,5	<1	<1	<0,2
JD-003		<1	40		69,9	535	4	64			<1	233	27	3	7		<2	<0,5			<0,1
JD-023A		<1	219		39,9	55	138	56			<1	57,7	256	13	16		<2	<0,5			<0,1
JD-030		<1	33		62,8	577	<1	17			<1	185	19	<1	11		<2	<0,5			<0,1
JM043R	36	0	222	0	24,1	1	112	36	19,4		0,7	1,3	330	11,6	8,5	1,8	0,3	0		0	0
JM085R1	47	0	143	0,02	24,1	2,4	6	13	12		0,5	1,7	209	11,2	17,5	0,8	0,4	0		0	0
VR197R	33	0	200	0,1	46,2	33,5	72,6	15	9,7		0,7	20,8	22	9,3	32,3	1,3	0,5	0		0	0
VR203R	37	0	191	0,05	43,2	9,9	4,5	9	13,4		0	0	189	4,8	4,9	0	0,2	0		0	0
VR222R	9	0	56	0,02	69,6	117	12,8	3	10,8		0	0	73,5	3,4	7,7	0,7	0	0		0	0

Muestra	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	W	Tl	Pb	Bi	Th	U
706332	8	0,5	1,1	0,2	1	0,3	0,2	0,4	0,1	0,6	0,1	0,3	0,1	0,4	0,1	0,4	<0,01	<0,5	<0,05	<5	<0,1	<0,05	0
706333	15	1,6	3,2	0,4	1,8	0,6	0,2	0,7	0,1	0,9	0,2	0,6	0,1	0,6	0,1	0,4	0,1	0,5	<0,05	<5	<0,1	<0,05	0,1
706334	16	1,1	2,5	0,3	1,4	0,4	0,2	0,5	0,1	0,6	0,1	0,4	0,1	0,4	0,1	0,3	0	<0,5	<0,05	<5	<0,1	<0,05	0
706336	34	1,7	4,1	0,7	3,8	1,3	0,5	1,6	0,3	1,5	0,3	0,8	0,1	0,7	0,1	0,6	<0,01	0,8	<0,05	<5	<0,1	<0,05	0
706337	32	1,3	3,2	0,5	2,6	0,8	0,4	1,1	0,2	1,3	0,3	0,8	0,1	0,9	0,1	0,5	0	0,9	<0,05	<5	<0,1	<0,05	0
706338	23	0,8	1,7	0,3	1,4	0,5	0,3	0,7	0,1	0,9	0,2	0,6	0,1	0,6	0,1	0,3	<0,01	<0,5	<0,05	<5	<0,1	<0,05	0
706340	8	0,5	1,3	0,2	1,2	0,4	0,2	0,6	0,1	0,7	0,1	0,4	0,1	0,5	0,1	0,4	0	<0,5	<0,05	<5	<0,1	<0,05	0
706343	11	0,6	1,4	0,2	0,8	0,2	0,2	0,2	0	0,2	0,1	0,1	0	0,1	0	<0,1	<0,01	<0,5	<0,05	<5	<0,1	0,1	<0.01
706345	109	0,3	1	0,1	0,6	0,2	0,1	0,3	0,1	0,4	0,1	0,2	0	0,2	0	0,2	<0,01	<0,5	<0,05	<5	<0,1	0,1	<0.01
706345	8	0,3	0,9	0,1	0,5	0,2	0,1	0,3	0,1	0,3	0,1	0,2	0	0,3	0	<0,1	<0,01	<0,5	<0,05	<5	<0,1	<0,05	<0.01
706346	22	1,1	4,3	0,7	3,7	1,2	0,4	1,5	0,3	1,6	0,3	1	0,2	1	0,1	0,5	<0,01	0,7	<0,05	<5	<0,1	<0,05	<0.01
JD-003	9	0,5	2		<1	0,2	0,2		<0,1					0,2	<0,001	<0,2	<0,3	<1		<5	<2	<0,1	<0,1
JD-023A	24	2	6		7	1,8	0,6		0,3					1,3	0,2	<0,2	<0,3	<1		<5	<2	<0,1	<0,1
JD-030	15	0,7	1		<1	0,2	0,3		<0,1					0,2	0	<0,2	<0,3	<1		<5	<2	0,2	<0,1
JM043R	47	3,9	9,1	1,5	7,1	2	0,8	2,3	0,4	2,3	0,4	1,2	0,2	0,9	0,1	0	0	1,1	0	0,1	0	0,3	0
JM085R1	76	1,8	4	0,6	3,6	1,1	0,5	1,9	0,3	2	0,4	1,3	0,2	0,9	0,2	0	0	2,4	0	0,2	0	0,2	0
VR197R	332	4,1	9,1	1,3	6	1,5	0,5	1,6	0,3	1,5	0,3	1	0,2	0,8	0,2	0,8	0	1,5	0,1	0,8	0	1,3	0,2
VR203R	17	0,9	2,1	0,3	1,5	0,5	0,3	0,7	0,2	0,9	0,2	0,6	0,1	0,6	0,1	0	0	0,9	0	0,3	0	0	0
VR222R	13	0,6	1,7	0,3	1,2	0,3	0,2	0,5	0,1	0,5	0,1	0,4	0,1	0,4	0,1	0	0	0,1	0	0,2	0	0	0

As far as Th concentrations are concerned, some of the samples have concentrations that are below the detection limit of the instruments used for its acquisition. In such cases we decided to use the ad hoc value of half the detection limit, i.e., 0.025ppm. In any case, in the diagram the boundary between tholeiitic and calcoalkaline rocks is Th = 0.245, hence all samples that yielded low Th plot within the tholeiitic field. In fact, 18 samples plotted in that field and only one in the calc-alkaline field. Of the 18 tholeiitic samples, 12 plot as basalt, the remainder six plot in the basaltic andesite and andesite fields.

When plotting the samples in the modified Zr/Ti vs. Nb/Y diagram (FIGURE 8B; Winchester and Floyd, 1977; Pearce, 1996), 17 plot in the basalt field, two in the andesite field, and all samples plot within the subalkaline field of mantle-derived rocks.

Based on the above discussion, we conclude that the Pantanillo Granulite belongs to a tholeiitic-komatiitic series. But, as was mentioned, the diagrams used to classify the rocks do not include a field for ultramafic rocks; hence, some of the rocks that plot in the basalt field may be gabbros transitional to ultramafic rocks, or if protoliths were extrusive rocks, picrites or komatiites, as is shown in the R1-R2 diagram.

In regard to tectonic environment, all 18 samples plot in the low-Ti tholeiitic island arc of the Ti vs. V diagram of Shervais (1982) (FIGURE 9A); one of the samples plots in the oceanic crust field. The Ti-V-Sc and Ti-V-Sm diagrams yield a similar result (Vermeesch, 2006) (FIGURE 9B). The multielement diagram normalized to N-MORB (Pearce, 1982) shows a negative Nb anomaly with respect to Th. This feature is characteristic of island arc tholeiitic basalt that is formed by dehydration and partial melting of subducted crust. In that process, Th and Ce are transferred from the subducted plate to the magma chambers below the arc, while Nb remains in the amphibole and minor phases of the subducted plate (Pearce, 1996). The rocks show relative depletion of REE's when compared with N-MORB, which is a characteristic feature of tholeiitic arcs. The Nb anomaly also support the previous conclusion, ie., that the protolith of the Pantanillo Granulite formed in a supra-subduction environment. The positive Eu and Sr anomalies (REE and multielemental diagrams) suggests that plagioclase formed early and was fractionated from the magma, perhaps by settling down of crystals in a magma chamber or early crystallization of phenocrysts (FIGURES 10A and 10B).

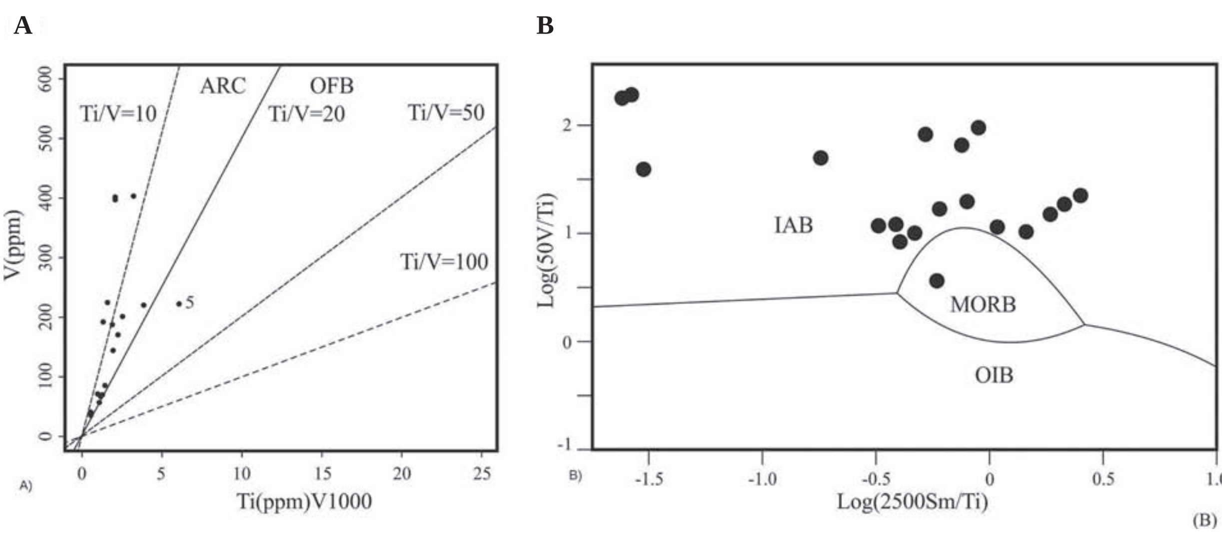

FIGURE 9. Pantanillo Granulite on tectonic discrimination diagrams: **A**) Ti vs. V tectonic discrimination diagram (Shervais, 1982); **B**) Ti-V-Sm diagram (Vermeesch, 2006).

The multielemental diagram shows that mobile trace elements are enriched and that immobile elements are not. The latter show a relatively horizontal pattern similar to MORB but somewhat more depleted.

The chondrite-normalized rare-earth-element diagram (McDonough and Sun, 1995); FIGURE 10B shows a relatively flat pattern with positive Eu anomaly in the most primitive rocks. Likewise, the patterns show a slight depletion of heavy rare-earth elements respect to the light ones. The rocks contain 1-10x chondrite concentrations suggesting a primitive mantle source depleted in REE's, more depleted than N-MORB, but parallel to MORB.

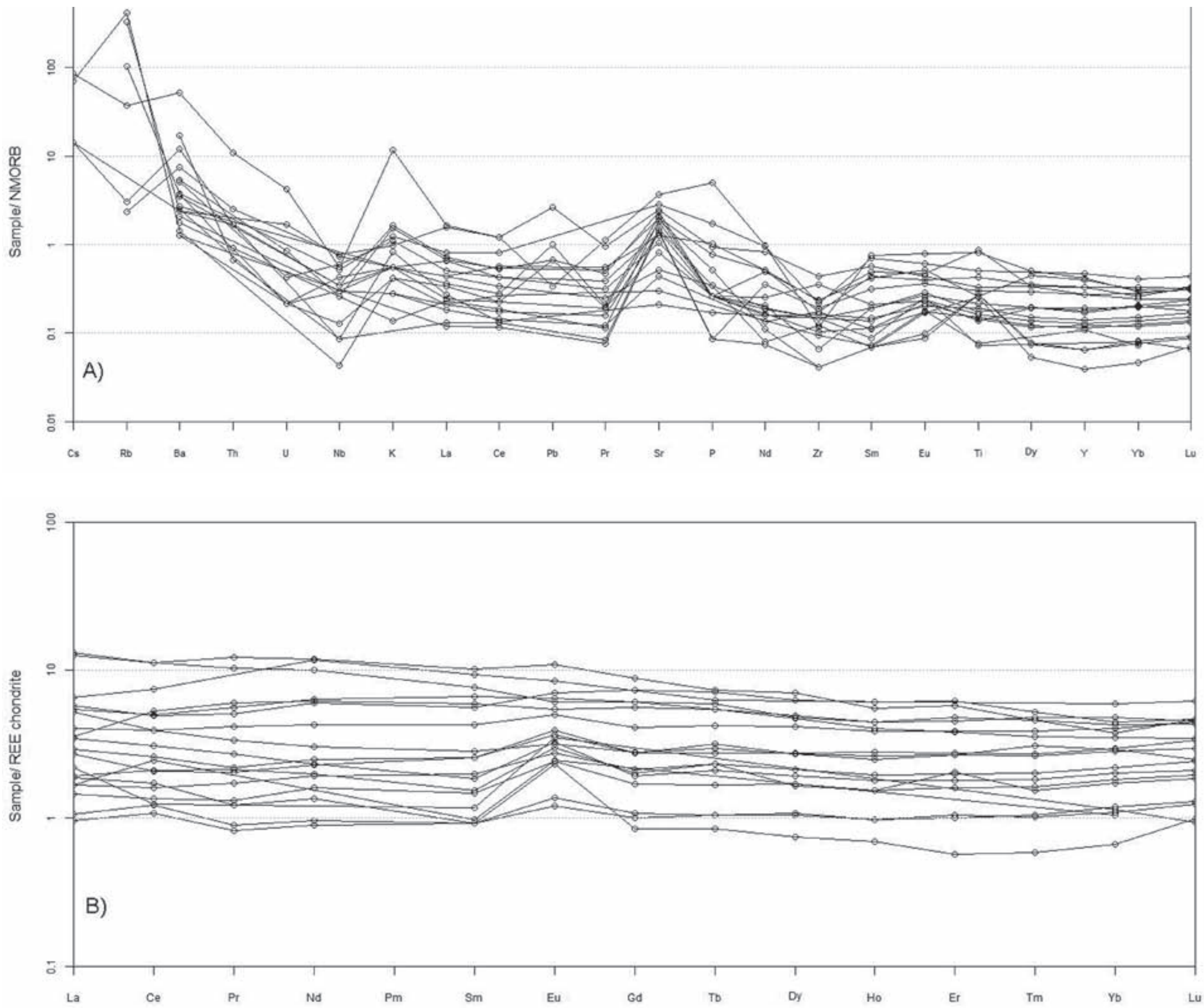

FIGURE 10. Multielemental and REE diagrams of Pantanillo Granulite. **A**) Trace-element diagram normalized to N-MORB; **B**) Chondrite-normalized REE diagram.

GEOCHRONOLOGY

Two geochronological analyses were conducted on Pantanillo Granulite: one is a whole rock, step-heating 40Ar-39Ar age, and the second is an amphibole K/Ar age. The resulting ages are listed in TABLE 4 and the step-heating experiment is depicted in FIGURE 11.

TABLE 4. Radiometric ages of Pantanillo Granulite.

SAMPLE	X	Y	UNIT	METHOD	TFA	WMPA	Ca/K
IGM-706332	1222750	1134764	Pantanillo Granulite	Ar-Ar whole rock	**216.2±14.2**	**206.5±9.2**	149.3-1017.7
JJ0003	1222816	1135252	Pantanillo Granulite	K-Ar amphibole	**360.7**±12.4		

TFA: Total fusion age
WMPA: Average plateau age

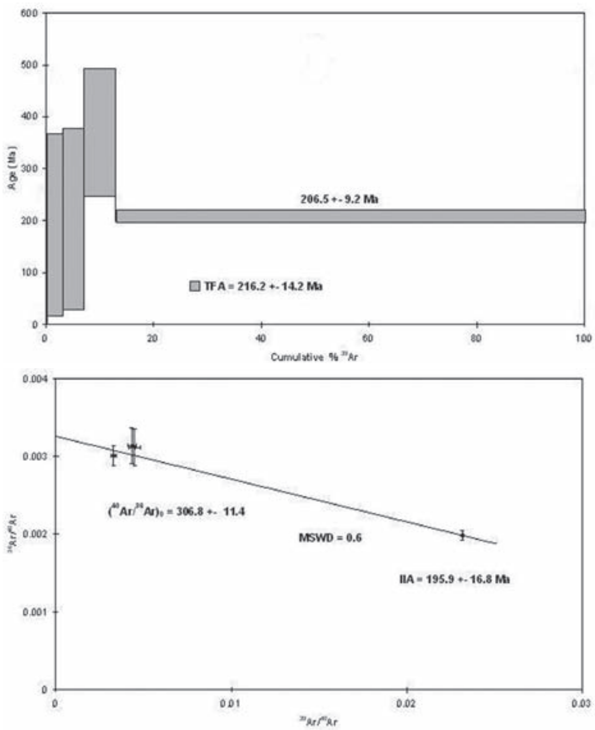

FIGURE 11. 40Ar/39Ar age spectrum and isochronic diagram of sample IGM-706332.

The spectrum obtained for sample IGM-706332 is dominated by one high-temperature step that yielded 87% of 39Ar and has an apparent age of 206.5 ± 9.2 Ma. All analyses define a reasonably well-constrained isochron of 196 ± 17 Ma, MSWD = 0.6. FIGURE 11 shows the age spectrum and isochronic diagram of sample IGM-706332, which is an olivine-bearing mafic granulite.

Hornblende separated from sample JJ-003 yielded a 360.7 +/- 12.4 Ma K/Ar age. However, the age may be affected by excess argon, inasmuch as the amphibole contains only 0.054% K. The large difference between the two ages is hard to interpret and these may or may not have geologic meaning.

DISCUSSION AND CONCLUSIONS

The mineral assemblages, textures, and structures observed in the Pantanillo Granulite show that this geologic unit underwent high-grade, granulite-facies metamorphism at low pressure. The granulites occur in the northern portion of the Western Cordillera, and they are spatially associated with the Sabanalarga Batholith. Locally, the unit contains amphibolite-facies paragenesis.

The fact that the granulites occur on both the western and eastern margins of the faults that run along Cauca River suggests that the Sabanalarga is a single batholithic unit. This conclusion contrasts with ideas of previous authors that distinguish between distinct western and eastern plutonic rocks.

Geochemically, the protolith of the granulites is characterized by mafic to ultramafic compositions. At this stage, it is difficult to establish whether the protolithic magma was troctolitic or picrite basalt.

The major-element geochemistry of Pantanillo Granulite shows affinity with tholeiitic basalt rich in Mg or komatiitic basalts of the sub-alkaline series. Trace-element geochemistry is consistent with tholeiitic arc. And the relatively flat pattern of the multielemental diagram is similar to that of N-MORB.

The K/Ar hornblende and 40Ar/39Ar whole-rock ages of the Pantanillo Granulite are not consistent. They may suggest a pre-Jurassic origin for the unit if the absence of an extraneous Ar component can be demonstrated. Although plausible, further work is needed before a correlation with the Triassic metamorphic rocks of the Central Cordillera can be robustly demonstrated.

The presence of the Pantanillo Granulite poses a problem to many classical models that show that to the west of the Cauca-Almaguer Fault only oceanic rocks without metamorphic rocks are found. If the Pantanillo Granulite formed as part of the Central Cordillera basement, they could have been dragged up by the magma of the Sabanalarga Batholith after been torned up from the western end of the Central Cordillera. Thus, by this time the continental and oceanic realms would already be amalgamated.

ACKNOWLEDGMENTS

The authors express their gratitude to the Instituto Colombiano de Geología y Minería, INGEOMINAS (current Servicio Geológico Colombiano), for providing and allowing the publication of petrographic, geochemical, and geochronological data obtained in the Cauca-Romeral and Western Cordillera projects.

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Trabajo recibido: Marzo 22 de 2012
Trabajo aceptado: Noviembre 30 de 2012