


Geology and petrology of the Salto do Céu Suite: tectonic and stratigraphic implications on the SW Amazonian Craton

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ABSTRACT: *The basic rocks of the Salto do Céu Suite outcrop as sills and flows in the southwestern Amazon Craton, Rondonian-San Ignacio Province, with an age of about 1.44 Ga. Sills are 2 to 30 m thick being hosted by pelites of the Aguapeí Group. The flows are up to 5 m thick and cover this unit. Typical textures of magma mingling are observed near the contact with granites of Rio Branco Suite. The Rio Branco Intrusive Suite is composed of basic and acid rocks, as well as hybrid rocks that indicate mixing processes between basic and acids magmas. U-Pb (TIMS zircon) results indicate ages around 1.4 Ga for both terms. The Salto do Céu Suite rocks have tholeiites affinity classified as subalkaline and iron-rich tholeiitic basalts, with mg# values between 0.30 and 0.51. They can be separated into two groups, based on La_N ; one is richer in ETR with La_N greater than 100, while the other one has La_N less than 100. Rocks of the Salto do Céu Suite and Rio Branco Suite are interpreted as a bimodal suites showing magma mingling features such as those developed in continental intraplate settings, extensional regime associated to the Columbia/Nuna breakup.*

KEYWORDS: mafic flows and sills; petrogenesis; extensional tectonics; Amazonian Craton.

INTRODUCTION

The mafic sills found in the region of Salto do Céu municipality, state of Mato Grosso, central Brazil, belonging to the Salto do Céu Suite (SCS) are interpreted as a record of the breakup of the Rodinia Supercontinent (Ruiz *et al.* 2010a, Lima *et al.* 2012) on the basis of K-Ar analyses that yields a cooling age around 0.9 Ga (Barros *et al.* 1982). Recent U-Pb (TIMS) analyses on baddeleyite show crystallisation ages around 1.44 Ga (Teixeira *et al.* 2016). This new geochronological result challenges the widely accepted geological history of the SW Amazonian Craton both in terms of this magmatic event of basic nature as well as the age of its country rock, that is, the Aguapeí Group. Distensive magmatic events, with ages similar to those obtained for the Salto

do Céu Suite, have been associated with the evolution of the Columbia Supercontinent by many authors (Ernst *et al.* 2008, 2013, Rogers & Santosh 2002).

The Rio Branco Intrusive Suite comprises basic (gabbro, diabase and basalt) and felsic (porphyritic and rapakivi granite) rocks. Hybrid rocks (monzosyenite) with rapakivi-like textures indicate commingling and mixing among basic and felsic magmas. U-Pb isotopic data indicate ages close to 1.4 Ga for both terms (Geraldes *et al.* 2004), situated in the Rondonian-San Ignacio geochronological province (Bettencourt *et al.* 2010).

Based on field work and new geochronological data available in the literature, as well as in unpublished petrographic and geochemical results of rocks from the SCS, the petrogenetic evolution of this mafic magmatism is discussed,

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as well as its relationship to felsic rocks of the Rio Branco Intrusive Suite (RBIS), and its tectonic implication to the evolution of the southwestern Amazonian Craton.

REGIONAL GEOLOGICAL SETTINGS

The south-southwest portion of the Amazonian Craton records a widespread occurrence of mafic sills and dyke swarms (Fig. 1) which have been interpreted as evidence for the breakup of the Rodinia Supercontinent (Ruiz *et al.* 2010a, Século *et al.* 2011, Lima 2011, Lima *et al.* 2012).

Gabbros and diabases found in the regions of Salto do Céu and Rio Branco, southwest of the Brazilian state of Mato Grosso, were first reported by Oliva (1979), and later attributed to the Rio Branco Group by Barros *et al.* (1982). Leite *et al.* (1985) have attributed this exposure of mesocratic and melanocratic rocks of the Rio Branco Intrusive

Suite to windows in the Vale da Promissao Formation cut by erosion. Therefore, these rocks are described as a differentiated stratiform igneous complex with typical bimodal character, which may be an indicative of anorogenic magmatism likely developed in rift settings.

According to Geraldes (2000) and Geraldes *et al.* (2001, 2004), the basal portion of the Rio Branco Intrusive Suite is composed of basic rocks, while its upper portion comprises a plutonic-volcanic association chiefly composed of acid to intermediate rocks. These authors presented a U-Pb age of 1471 ± 8 Ma for basic rocks, and an age of 1427 ± 10 Ma for acid rocks that are interpreted as an extensional intracratonic magmatism, a reflection of the Santa Helena magmatic arc (1.47–1.42 Ga).

The Santa Helena magmatic arc is characterized in a precocious phase (1480–1485 Ma) by calc-alkaline batholiths, peraluminous, tonalitic and monzogranitic (Santa Helena and Água Clara Intrusive Suites) and by minor bodies of

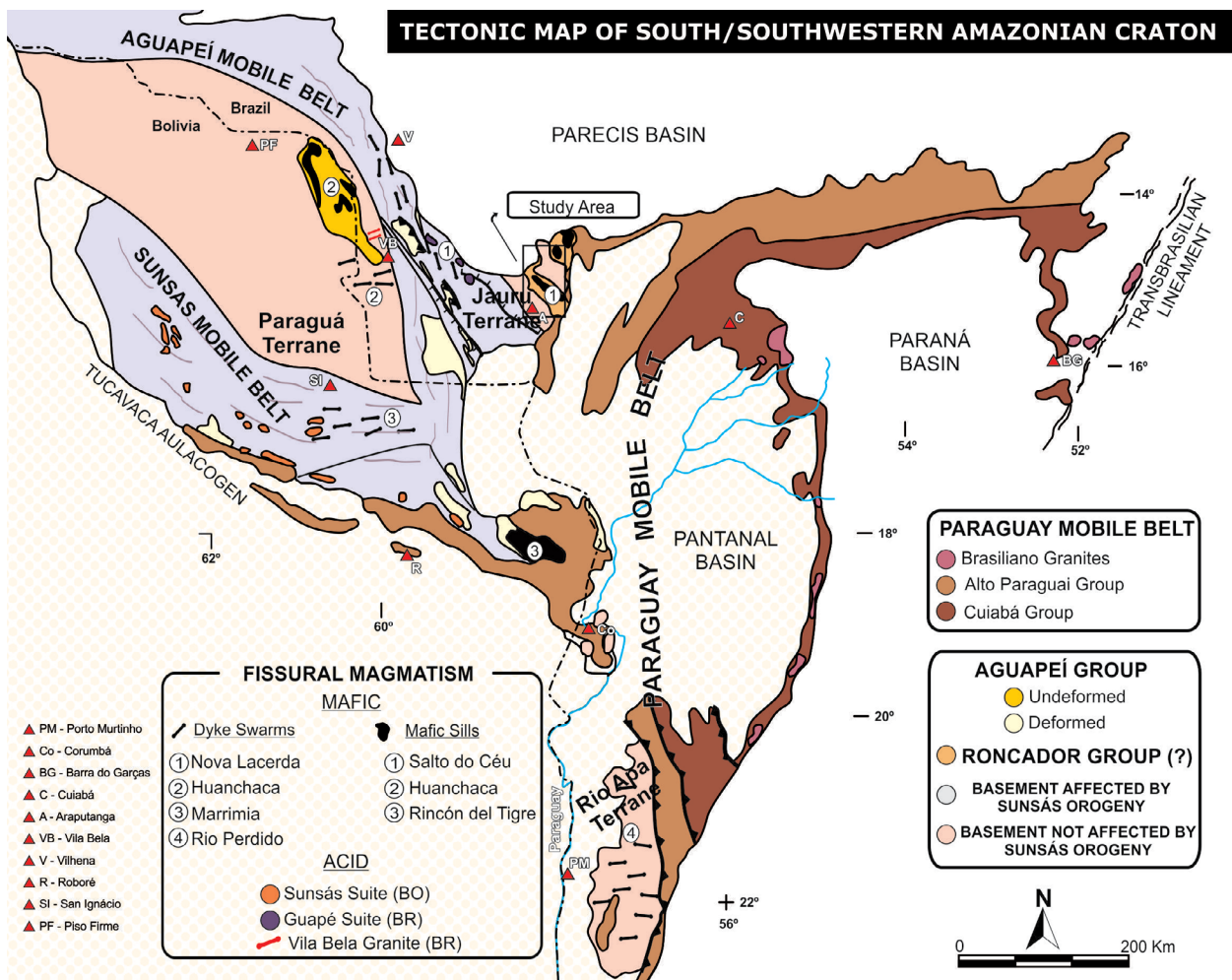


Figure 1. Tectonic Map of the South/Southwestern Amazonian Craton highlighting the fissural mafic magmatism (dykes of the intrusive suites Rio Perdido, Nova Lacerda and Huanchaca; and sills of the Salto do Céu and Huanchaca intrusive suites), and felsic magmatism (plutons of the Guapé Intrusive Suite and granitic dykes of the Vila Bela Granite). Extracted and modified from Ruiz *et al.* 2010b.

the Intrusive Suite Pindaituba (1465–1425 Ma), with large compositional variation (Ruiz 2005).

Araújo *et al.* (2005) named as Salto do Céu Intrusive Suite the assemblage of intrusions occurring parallel to the bedding of pelites and psammites of the Vale da Promissão Formation (Aguapeí Group), and composed of mafic sills 1 to 5 m thick. Araújo-Ruiz *et al.* (2007) recognized two main plutonic series in the Rio Branco Intrusive Suite, one of basic nature with discontinuous distribution located in the intrusion borders, and another one of acid/intermediate nature that is composed of three petrographic facies. It was concluded that the occurrence of gabbroic rocks represent two separate magmatic events: the basic plutonic rocks (gabbros and diorites) belonging to the Rio Branco Intrusive Suite, and the shallow intrusions (diabases, microgabbros) belonging to the Salto do Céu Intrusive Suite.

Araújo (2008) obtained U-Pb (TIMS) ages of 1403 ± 0.6 Ma and 1382 ± 49 Ma for the intermediate to acid rocks, interpreted as the time of igneous crystallization for felsic magmas that gave rise to the Rio Branco Intrusive Suite.

The Rio Branco Intrusive Suite, as reported by Araújo *et al.* (2009) and Araújo & Godoy (2011), comprises two main plutonic suites: the Rio Branco Basic Intrusive Suite that is composed of basic to intermediate rocks, and the Rio Branco Acid Intrusive Suite which is intermediate to acid in composition. Also, according to these authors, the gabbroic association comprises two temporally distinct magmatic events: the first one is composed of basic to intermediate plutonic rocks, such as microgabbros to diabases, monzogabbros, and quartz-monzonites to quartz-diorites that are grouped into the Rio Branco Basic Intrusive Suite; the other magmatic event include hypoabissal lithotypes, such as diabases and microgabbros, occurring as sills hosted by the Aguapeí Group, and grouped together under the name of Salto do Céu Basic Intrusive Suite.

Based on more detailed geological mapping, Sousa *et al.* (2017) assigned the term Rio Branco Intrusive Suite only to acid to intermediate rocks, thus assigning all the basaltic and gabbroic rocks to the Salto do Céu Intrusive Suite.

Teixeira *et al.* (2016) obtained U-Pb baddeleyite ages of 1439 ± 4 Ma for the Salto do Céu sills, and of 1387 ± 17 Ma for the Nova Lacerda mafic dyke swarms. These ages reflect a single magmatic event for these units associated with the evolution of the Columbia Supercontinent.

Mesoproterozoic sedimentary and metasedimentary rocks occurring in the southwest of Mato Grosso, and in Eastern Bolivia were first reported in the LASA report (1968). These rocks were latter named Aguapeí Unit by Figueiredo & Olivatti (1974). Souza & Hildred (1980) used the term Aguapeí Group in order to group the formations Fortuna, Vale da Promissão and Morro Cristalina,

which was then described as a marine transgressive-regressive platform cover sequence.

According to Saes (1999), the Fortuna Formation is composed of sandstones and orthoquartzitic conglomerates. These rocks with widespread cross-bedding indicates deposition in braided fluvial systems in the areas of Huanchaca and Sao Vicente Hills which eventually prograded into a shallow-marine platform influenced by tidal currents, fan deltas and tempestites in the region of Pontes and Lacerda, and Rio Branco. The Vale da Promissão Formation represents a progradational wedge of marine sediments thickening towards the SE. In the regions of Rio Branco, and Pontes and Lacerda, this unit consists of pelitic rocks intercalated with sandstones that were deposited by storms on shallow marine platform. The Morro Cristalina Formation is chiefly composed of quartz-arenites, and rarely composed of conglomerates whose main characteristics are the high level of maturity and the exclusive continental character (fluvial and eolian) of its deposits.

Geraldes *et al.* (2014) obtained U-Pb (LA-ICP-MS) ages on detrital zircons for samples from the Aguapeí Group collected in three hills: Rio Branco, Ricardo Franco and Santa Bárbara. The results from the Rio Branco Hill, same region where the target rocks crop out, yield four main age peaks at 1544, 1655, 1812 and 2515 Ma. According to these authors, the first peak is likely related to the rocks of the Cachoeirinha orogeny, the second peak represents the rocks of the Lomas Manechis Complex (Bolivia) and, in their turn, the last two peaks may represent the older units not mapped yet.

Table 1 shows geochronological data available for the acid to intermediate rocks and basic rocks, respectively, from the Rio Branco and Salto do Céu suites.

GEOLOGICAL AND PETROGRAPHIC CHARACTERIZATION

The basic rocks crop out in the study area as sills and lava flows, blocks or as large low-lying outcrops along drainages. The main outcrops are exposed on the road joining the town of Salto do Céu to the Progresso Village, on the upper reaches of the Bracinho Stream in the municipality of Rio Branco, and on the slopes of the homonymous hill (Fig. 2).

Locally, typical magma mingling features can be observed in the Rio Branco Suite outcrops. These features consist of mafic microgranular enclaves within the felsic rocks (Figs. 3A and 3B). The mafic microgranular enclaves show alkali feldspar xenocrysts with reabsorption features and recurrent transitional and diffuse boundaries, and centimeter size hybridization zones in the contact with the felsic rock.

Mafic microgranular enclaves are pointed by Barbarin and Didier (1992) and Barbarin (2005) as indicative of magma mingling processes. The hybridization zone, restricted to the enclaves margins, indicates the subordinated actuation of mixing processes, commonly observed in granitoid evolved by magma interaction, as suggested by Barbey *et al.* (2008).

Sills are 2 to 30 m thick, and show well-defined intrusive contacts with pelites of Vale da Promissão Formation (Fig. 3C) as well as tectonic contacts with the sandstones of Morro Cristalina Formation as a result of normal faulting. They are gently dipping between 10° and 15° WSW, and in some places their dip is 5° toward both SW and ENE. The shape-rounded outcrops display typical spheroidal exfoliation.

Lava flows are about 6 m thick and show vertical internal structures as well as flow-top structures, typical of thin basaltic lava flows (< 10 m) as highlighted by Aubele *et al.* (1988) and Cashman & Kauahikaua (1997). Their internal structure is marked by zoning consisting of an upper vesicular portion (~ 1.7 m), and another intermediate portion without vesicular texture (~ 4.0 m); no vesicular lower portion was recognized as usual in the basaltic lava flows.

The abundance and size of vesicles increase toward the top (Figs. 4A and 4B). Flow folds (Figs. 4C and 4D) deformed during lava flow motion result in surfaces of pahoehoe flows observed at the top of flows (30 to 40 cm below the top). The deformation caused by lava flow motion also led to fragmentation of ropy lava in the upper crusts resulting in its brecciated aspect (Figs. 4E and 4F), in places showing rapakivi texture (Fig. 4G) and formation of alkali feldspar phenocrysts partially resorbed (Fig. 4H). Internal structures and flow-top aspects are characteristics similar to those pointed out by Chitwood (1994), Hon *et al.* (1994) and Self *et al.* (1998) for pahoehoe inflated flows deposited in subaerial settings. Vesicles are mostly filled with fibrous to fibro-radiated material consisting of zeolites chlorite, fluorite and opaque minerals.

Both sills and lava flows are mesocratic to melanocratic, greenish-gray to black in colour, and equigranular varying from very fine- to medium-grained.

The sills consist of diabases and massif gabbros that under the microscope display ophitic, subophitic, intergranular, and coronitic textures (Figs. 5A, 5B and 5C). They are essentially composed of plagioclase and pyroxene, having as accessory

Table 1. Geochronological and isotopic database for the acid to intermediate rocks (Rio Branco Suite) and basic rocks (Salto do Céu Suite).

	References	U-Pb	Rb-Sr		Sm-Nd		K-Ar
		Age (Ma)	Age (Ma)	(⁸⁷ Sr/ ⁸⁶ Sr) ₀	T _{DM} (Ga)	εNd(t)	Age (Ma)
Acid to intermediate rocks	Barros <i>et al.</i> (1982)	-	(WR) 1130 ± 72	0,708	-	-	-
	Ruiz (1992)	-	(WR) 1126 ± 39	0,7165	-	-	-
	Geraldes <i>et al.</i> (2001)	(Z) 1427 ± 10	-	-	1,89 a 1,79	-0,2	-
	Geraldes <i>et al.</i> (2004)	(Z) 1423 ± 0,2	-	-	1,89 a 1,81	-0,96 a +0,16	-
	Araújo (2008)	(Z) 1423 ± 06 (Z) 1380 ± 49	-	-	1,91 a 1,65	-1,78 a +1,24	-
	Sousa <i>et al.</i> (2017)	-	-	-	2,08	-3,39	-
Basic rocks	Hama (1976) <i>apud</i> Ruiz (2005)	-	-	-	-	-	(P) 1006 ± 16
	Barros <i>et al.</i> (1982)	-	-	-	-	-	(WR) 875 ± 21 (P) 878 ± 10 (P) 930 ± 14 (P) 960 ± 21
	Leite <i>et al.</i> (1985)	-	-	-	-	-	(P) 1015 ± 17
	Geraldes <i>et al.</i> (2001)	(Z) 1471 ± 08	-	-	1,86 a 1,73	-2,3	-
	Geraldes <i>et al.</i> (2004)	(Z) 1471 ± 31	-	-	1,86 a 1,73	-2,33 a +1,91	-
	Araújo (2008)	(S) 808 ± 620	-	-	1,74	+2,61	-
	Teixeira <i>et al.</i> (2016)	(B) 1439 ± 4	-	-	-	-	-

Z: zircon; S: sphene; B: baddeleyite; WR: whole-rock; P: plagioclase.

Occasionally, pyroxene shows complete pseudomorphism by amphibole, chlorite and biotite, but it may also occur as relict mineral.

The types of amphibole here observed are actinolite-tremolite and hornblende. Light green actinolite-tremolite occurs as acicular subhedral crystals, single crystals or fibrous aggregates that fills microvenules and microfractures following a fibroradiated arrangement. They are mainly associated to the borders of pyroxene featuring coronitic texture, and may completely replace the pyroxene. Brown hornblende is observed as anhedral grains or pseudomorphs of pyroxene. It is usually altered to biotite and chlorite that may replace it completely.

Opaque minerals (Figs. 7A and 7B) are common in these rocks as well-developed, subhedral, skeletal and symplectitic crystals, and may be partially replaced by biotite, chlorite, rutile and sphene.

Biotite is a common product from the alteration of amphibole, pyroxene or opaque minerals. These minerals are in places surrounded by a biotite fringe consisting of

tiny fibrous crystals. Biotite seldom occur as well-developed blades with reddish brown to brownish pleochroism. Chlorite is observed in thin microscopic greenish blades displaying a fibrous to fibro-radiated habit. Chlorite also occurs associated with amphibole in pseudomorphs of pyroxene and opaques, or in a pervasive way as fracture filling in plagioclase.

Lava flows consist of basalts exhibiting the following textures: ophitic, subophitic, hyalophitic, porphyritic or amygdaloidal in pseudo-trachytic groundmass (Figs. 8A, 8B and 8C); vitrophyric texture is also observed in some samples.

Their main components are plagioclase, pyroxene, and relict glass having as accessory and alteration paragenesis: amphibole, biotite, chlorite, opaque, rutile, sphalerite, apatite, sericite, epidote/clinozoisite, calcite and clay minerals.

The amygdales are round to ellipsoidal in shape, with diameter up to 3 mm, filled by fibrous to fibro-radiated material (Figs. 9A, 9B, 9C, 9D, 9E and 9F) consisting of zeolites, chlorite, fluorite (Figs. 10A and 10B) and opaque

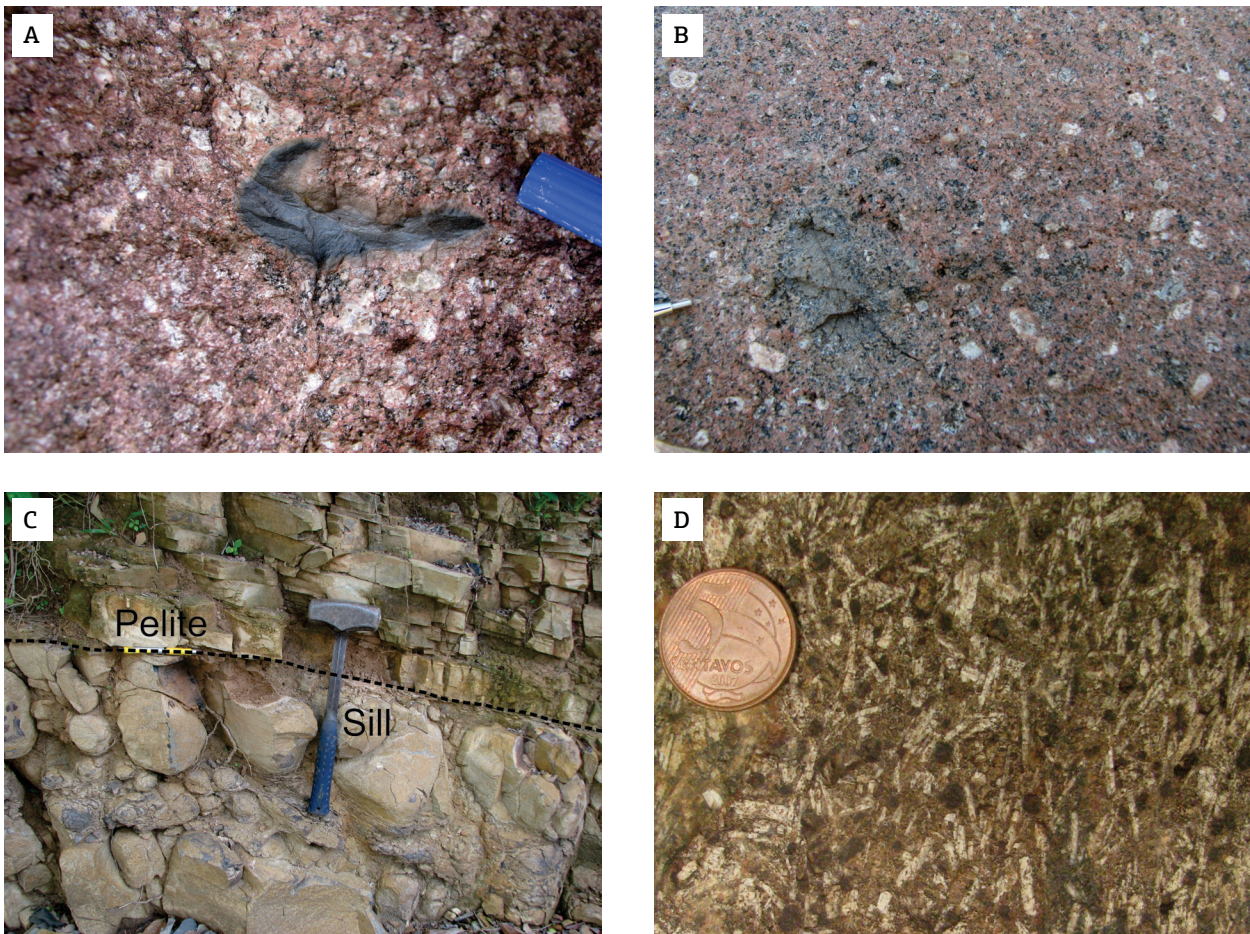


Figure 3. Field aspects of sills from Salto do Céu Suite: (A) mafic enclave likely from the Salto do Céu Suite enclosed in rocks of the Rio Branco Intrusive Suite; (B) hybridized areas resulting from interaction between felsic (Rio Branco Intrusive Suite) and mafic (Salto do Céu Suite) magmas; (C) concordant contact between sills of Salto do Céu Suite and laminated pelites of Vale da Promissao Formation; (D) macroscopic aspect of sills, with emphasis on subophitic texture marked by interstitial plagioclase laths between pyroxene crystals.

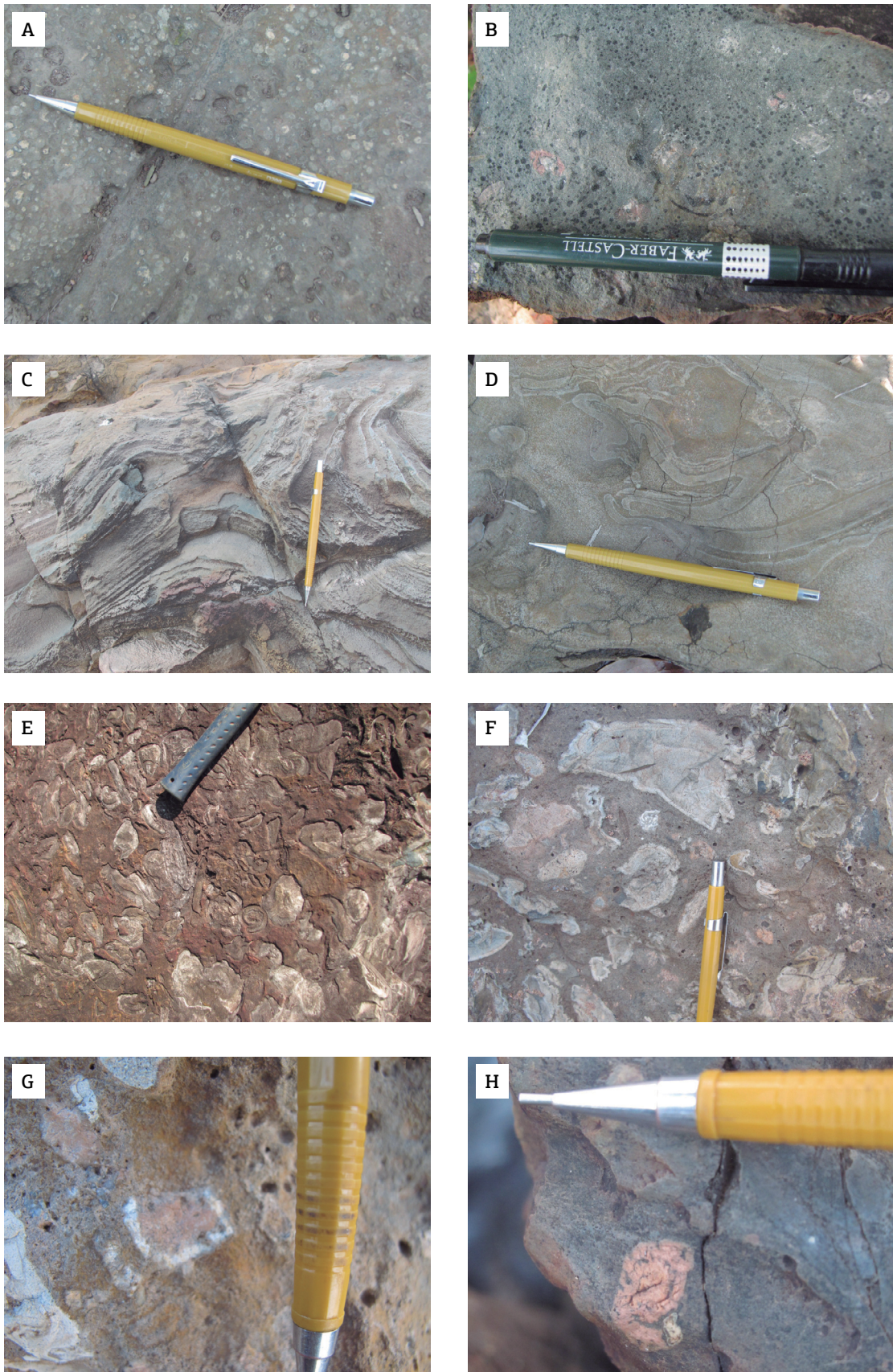


Figure 4. Field aspects of lava flows from Salto do Céu Suite: (A and B) large amount of round vesicles in the flow top; (C and D) flow folds; (E and F) brecciated aspect resulting from flow lava fragmentation as deformation occurs during its motion; (G) and H) alkali feldspar phenocryst displaying rapakivi texture and partially resorbed, respectively.

minerals. They may present reaction rims composed of a red-coloured mixture of iron oxides/hydroxides, biotite and rutile.

Labradorite/andesine occurs as euhedral to subhedral tabular phenocrysts and submillimetre-sized laths displaying albite, pericline and Carlsbad twinning.

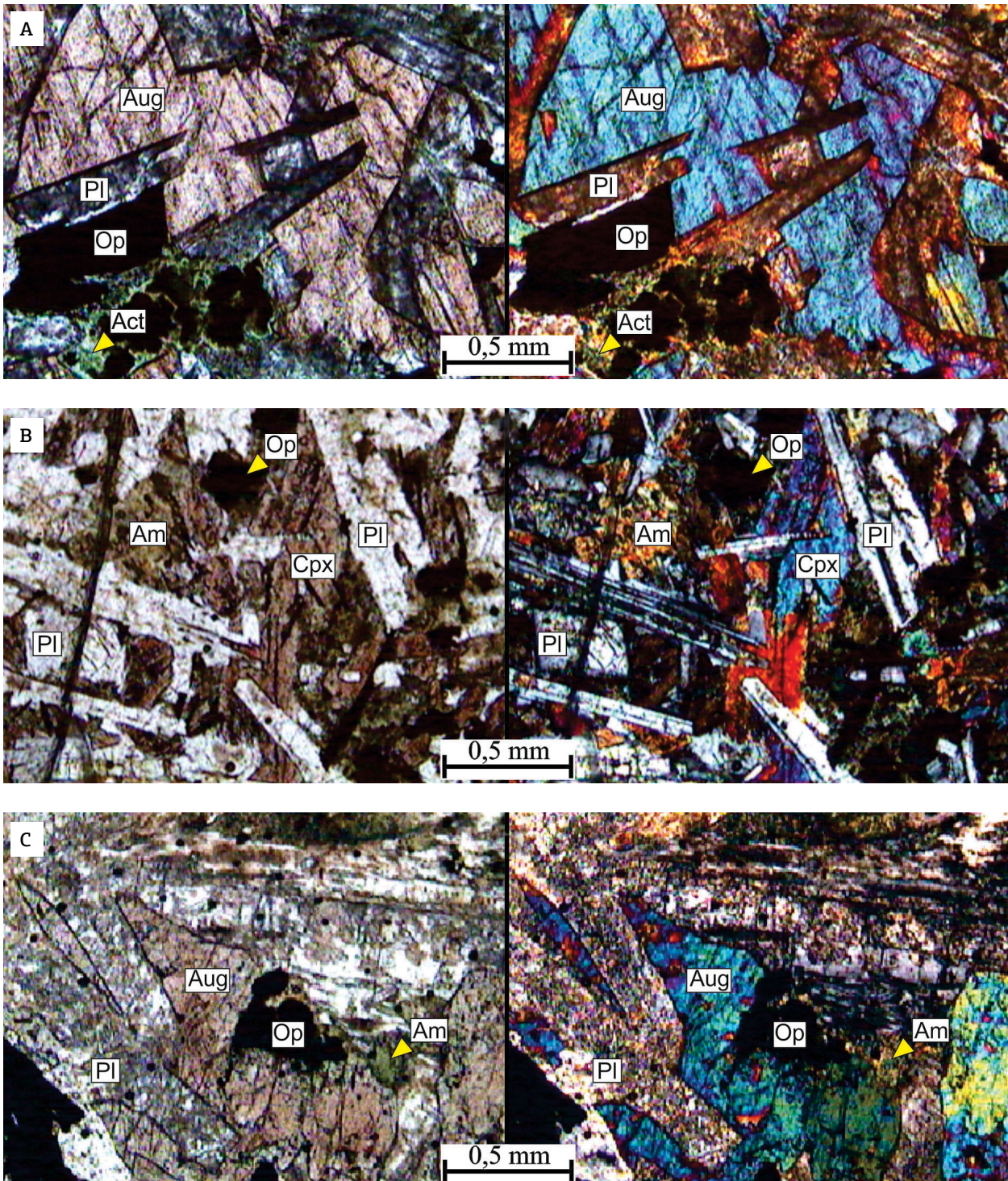


Figure 5. Photomicrographs of sills (gabbro) from Salto do Céu Suite displaying: (A) ophitic texture featured by pseudomorph augite (titanoaugite) crystal consisting of opaque minerals and actinolite, including intensely altered plagioclase laths; (B) tabular plagioclase between prisms and grains of pyroxene characterizing subophitic texture; (C) intergranular texture consisting of saussuritized tabular plagioclase crystals and partially unaltered interstitial pyroxene. Parallel polarizers to the left and crossed polarizers to the right. Abbreviations are as in Fettes & Desmons (2008).

Alteration processes such as argilization, sericitization, and mostly saussuritization are observed. Some crystals delineate a pseudotrachytic flow texture and may show

normal, oscillatory and reverse zoning recognized by its higher degree of saussuritization in the more calcium-rich portions of plagioclase.

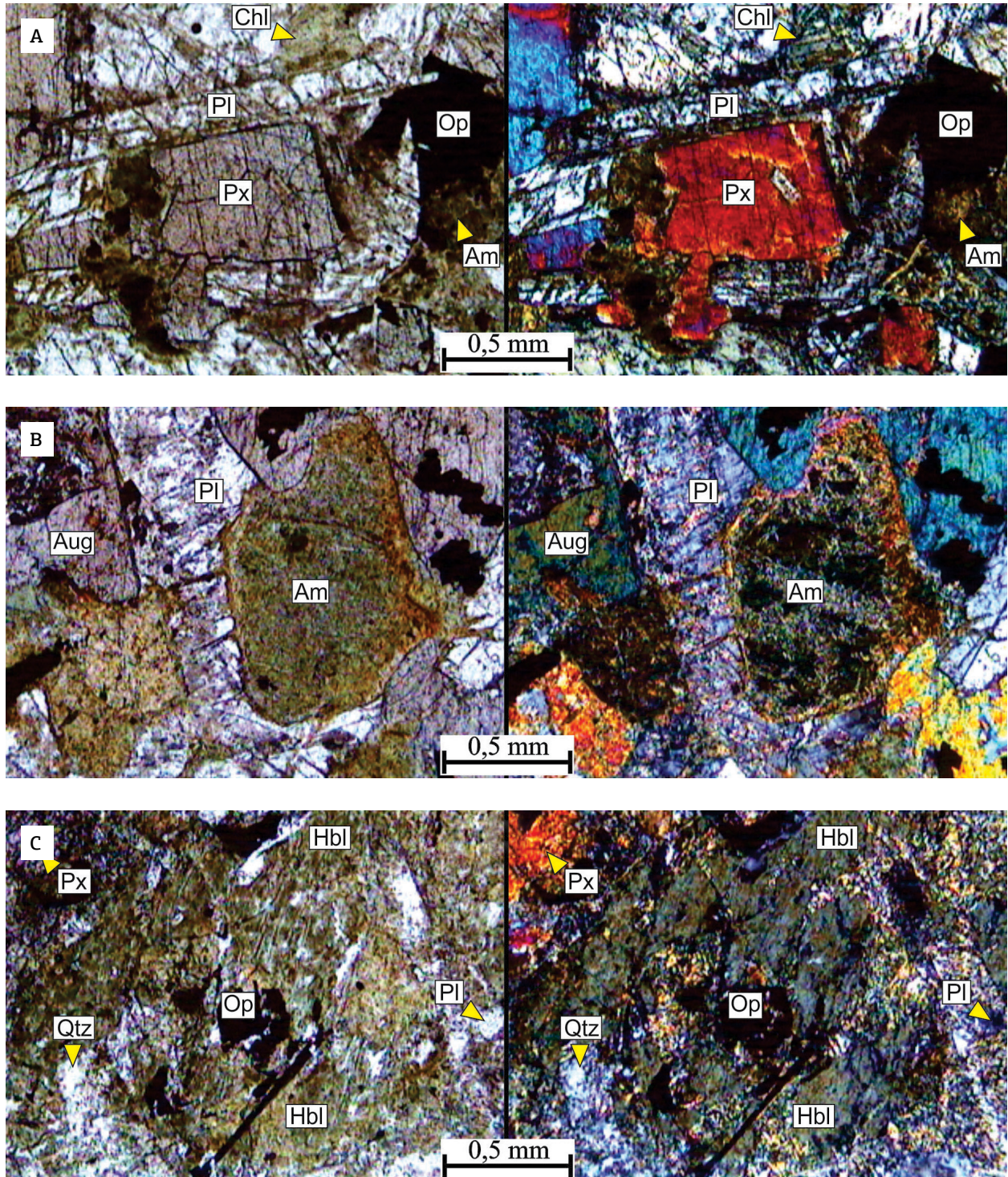


Figure 6. Photomicrographs of sills (gabbro) from the Salto do Céu Suite showing: (A) fractured plagioclase crystals, pyroxene and opaque minerals partially altered to amphibole, biotite and chlorite; (B) subophitic texture consisting of tabular plagioclase and augite crystals, some pseudomorphized by amphibole; (C) pseudomorph of amphibole (hornblende) after pyroxene associated with plagioclase, quartz and opaques. Parallel polarizers to the left and crossed polarizers to the right. Abbreviations are as in Fettes & Desmons (2008).

Clinopyroxene is identified as augite and pigeonite, white to pink in colour, in places exhibiting zoning and twinning, partially to completely uralitized or pseudomorphized by a mixture of amphibole, chlorite and biotite; some lithotypes contain orthopyroxene recognized as colourless to beige enstatite, partially altered to tremolite-actinolite and chlorite.

The amphibole types are products of pyroxene transformation occurring as hornblende prismatic crystals and grains, dark-green to brown in colour, and show drop-like quartz texture as well as acicular, fibrous and fibro-radiated, and white to greenish in colour tremolite-actinolite is seen. Both of them alters to biotite, chlorite and opaques.

Opaque minerals occur mostly as primary minerals or result from alteration of mafic minerals. They are more developed crystals showing dendritic habit and symplectitic texture, in places partially altered to biotite, chlorite, rutile, and sphene. Biotite occurs as tiny brown to brownish blades, sparsely distributed in the rock or in association with

amphibole. Rare biotite crystals are found well-preserved and often result from the alteration of opaque minerals.

Reaction border consisting of calcite in very fine-grained fluidal groundmass (Fig. 10C), and euhedral sphalerite phenocrysts displaying magmatic corrosion (Figs. 10D and 10E).

LITHOCHEMICAL CHARACTERIZATION

The lithochemical study of sills and lava flows from SCS was carried out on fourteen samples; also, sills and lava flows were studied together due to their chemical affinity. These samples were previously crushed and pulverized in the Sample Preparation Laboratory of the Geosciences College, Federal University of Mato Grosso, and forwarded to the Acme Analytical Laboratories (Vancouver, Canada) in order to measure major and minor elements, using ICP-ES, and trace-elements including rare earth elements using, ICP-MS.

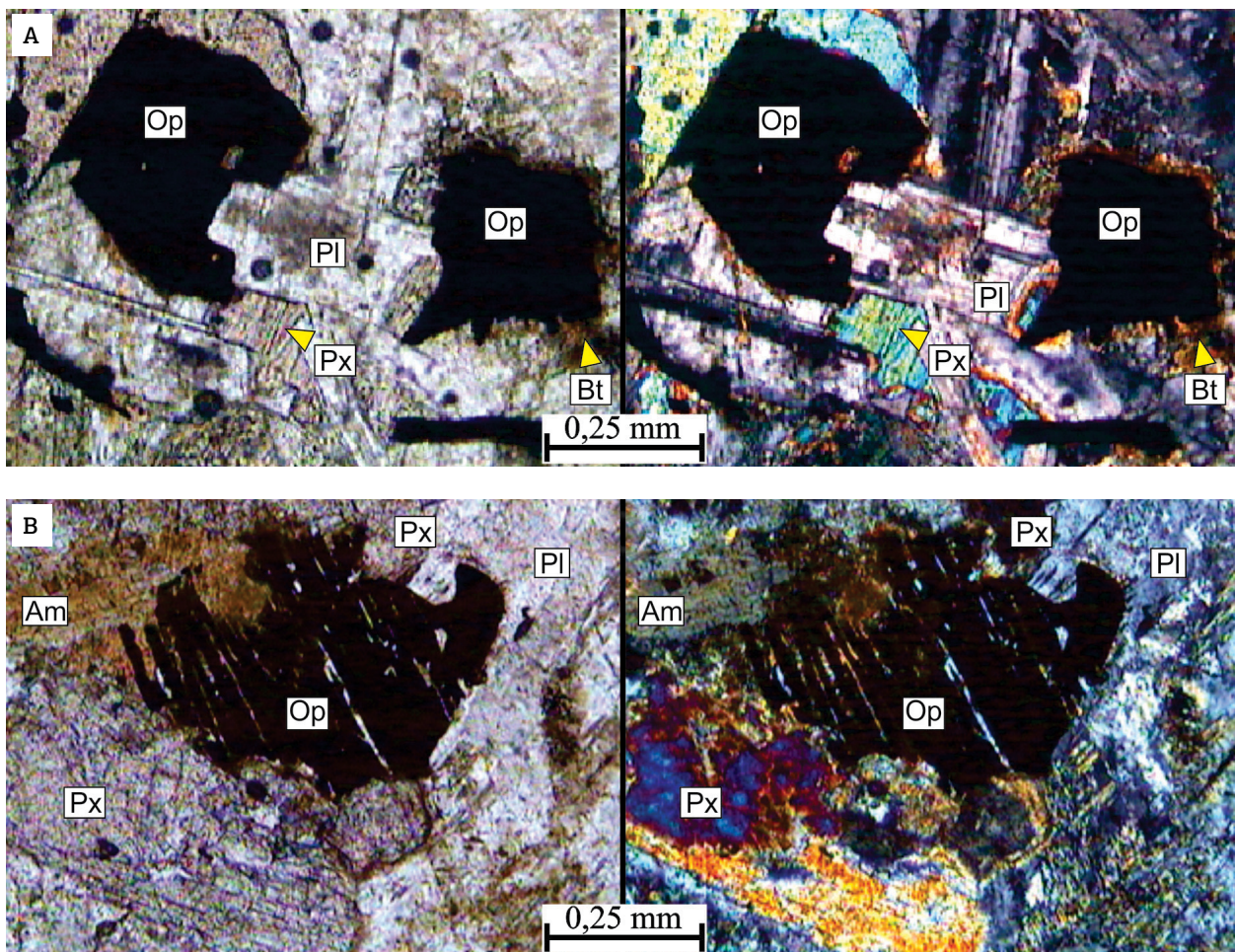


Figure 7. Photomicrographs of sills (diabase) from Salto do Céu Suite illustrating: (A) detail of opaque minerals with biotite corona and plagioclase showing normal zoning; (B) opaque mineral with symplectite texture associated with pyroxene, amphibole and plagioclase. Parallel polarizers to the left and crossed polarizers to the right. Abbreviations are as in Fettes & Desmons (2008).

Analytical data are shown on Table 2. Data processing was performed using GCDkit software (version 3.0, Geochemical Data Toolkit for Windows; Janoušek *et al.* 2006).

MgO contents vary between 3.75 and 6.86 %, and SiO₂ contents vary between 44.03 and 49.32%. Calculated mg# values [Mg/(Mg + Fe²⁺)] vary from 0.30 to 0.51 taking into

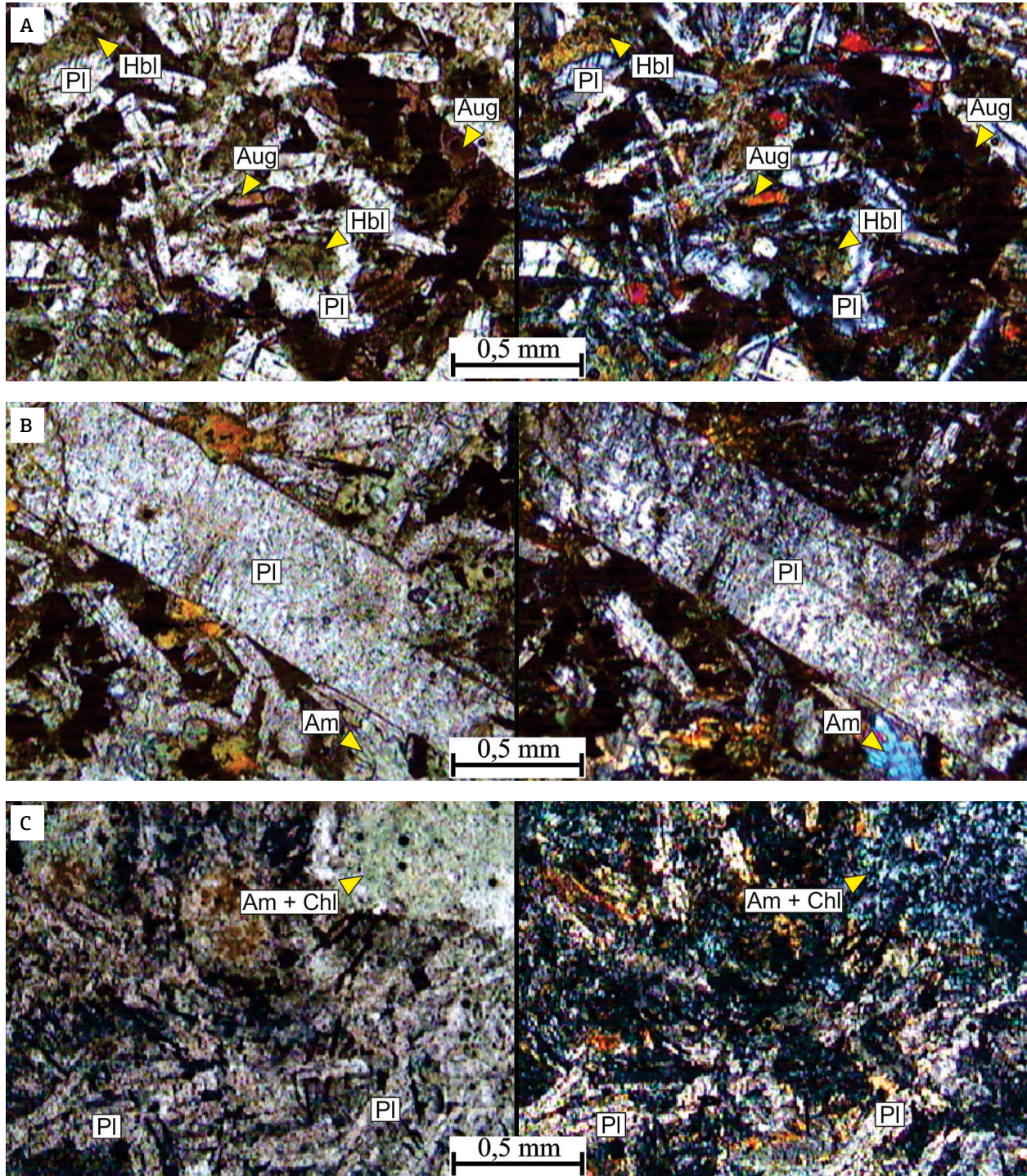


Figure 8. Photomicrographs of lava flows (basalt) from Salto do Céu Suite displaying: (A) ophitic to intergranular texture featured by plagioclase laths and dark-pink titanite with partial to complete replacement by green-coloured hornblende; (B) porphyritic texture formed by tabular plagioclase enclosed into a subophitic to intergranular groundmass; (C) fluidal groundmass showing pseudo-trachytic texture delineated by the arrangement of deformed plagioclase laths intercalated with mafic minerals, and amphibole pseudomorphs of original pyroxene. Parallel polarizers to the left and crossed polarizers to the right. Abbreviations are as in Fettes & Desmons (2008).

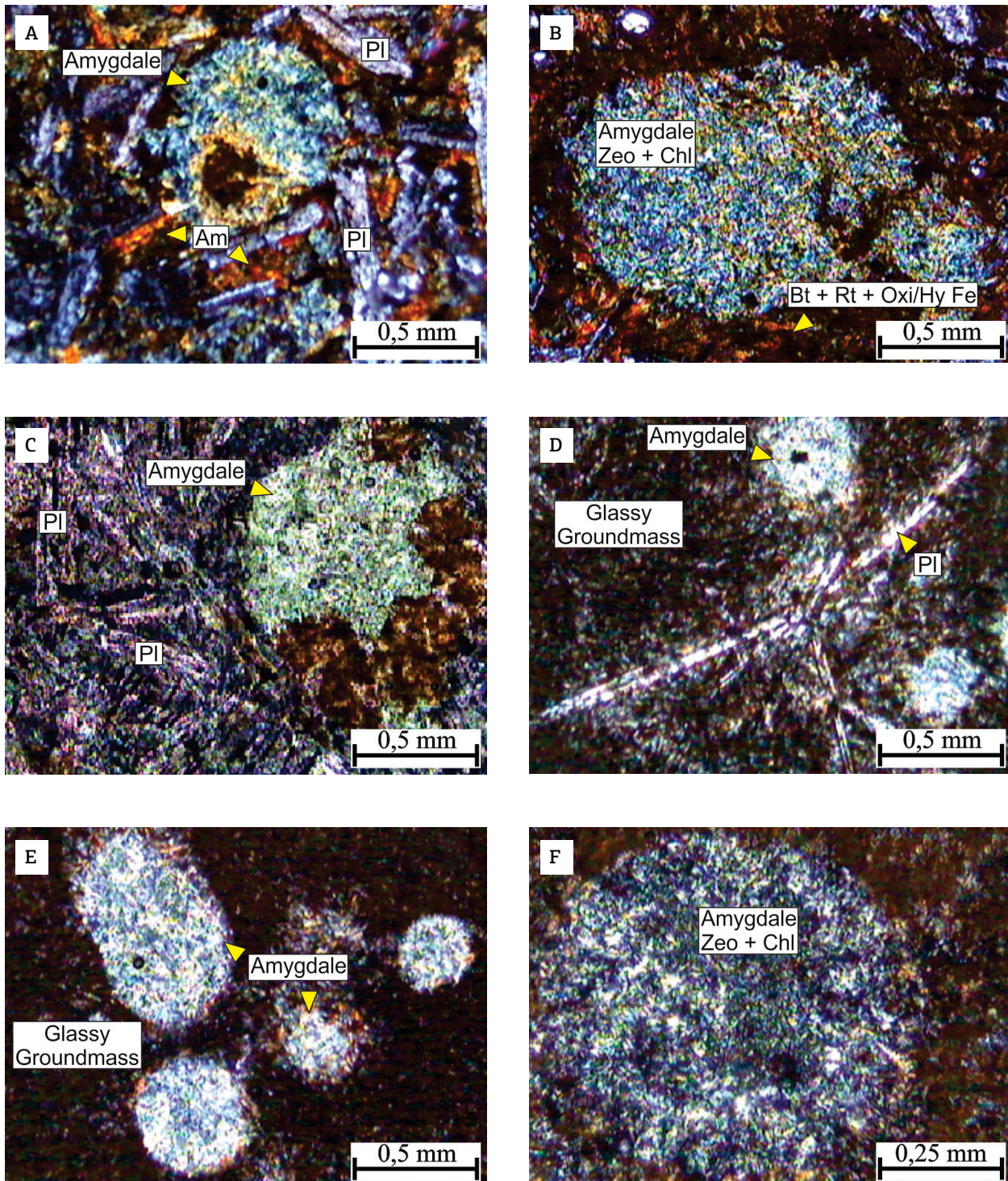


Figure 9. Photomicrographs of lava flows (basalt) from Salto do Céu Suite showing: (A) amygdale enclosed in subophitic groundmass with plagioclase laths and amphibole; (B) amygdale filled with zeolite and chlorite surrounded by a halo consisting of a mixture of biotite, rutile, and iron oxides/hydroxides; (C) amygdale filled with zeolite, chlorite, biotite, and iron oxides/hydroxides in fluidal groundmass; (D) vitrophyric texture formed by elongate laths of plagioclase phenocrysts and amygdale in glassy groundmass; (E) round and ellipsoidal amygdale in glassy groundmass; (F) Detail of rounded amygdale filled with zeolite and chlorite. Parallel polarizers in (C) and crossed polarizers in (A), (B), (D), (E) and (F). Abbreviations are as in Fettes & Desmons (2008).

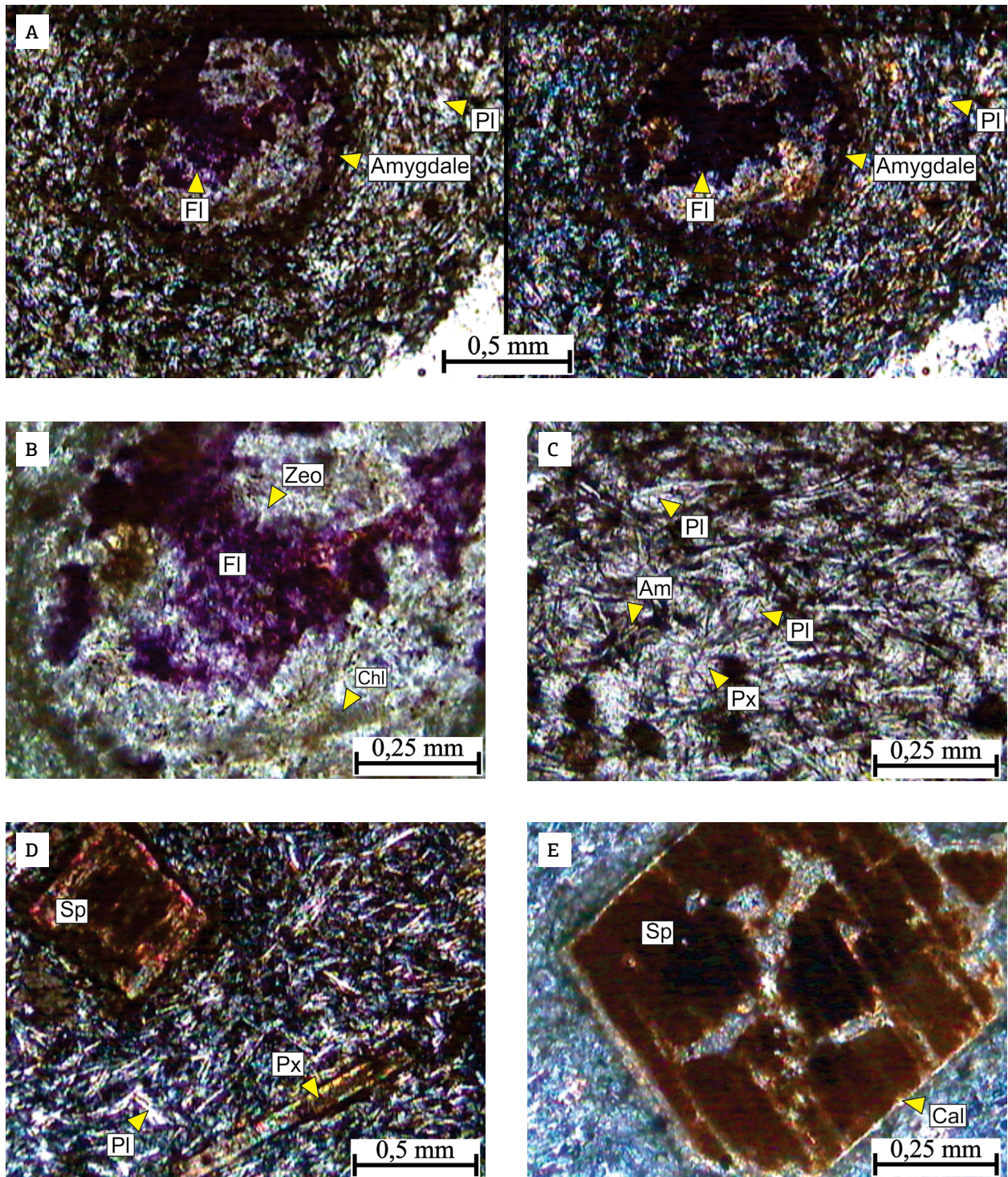


Figure 10. Photomicrographs of lava flows (basalt) from Salto do Céu Suite showing: (A) fine-grained groundmass with pseudo-trachytic texture marked by alignment of plagioclase laths and mafic minerals, and amygdale filled with secondary phases, such as fluorite, opaques, chlorite and zeolite; (B) details of groundmass highlighting the purple colour of fluorite; (C) detail of groundmass composed of plagioclase laths, pyroxene grains and amphibole; (D) sphalerite and pyroxene phenocrysts in a trachtyoid groundmass consisting of submillimetre-sized laths of plagioclase and mafic minerals; (E) detail of euhedral sphalerite crystal with magmatic corrosion and reaction rim of calcite. Parallel polarizers to the left and crossed polarizers to the right in (A), parallel in (B) and (C), and crossed polarizers in (D) and (E).

Table 2. Lithochemical data of rocks from Salto do Céu Suite [major elements (% weight), trace-elements (ppm)].

	#RB 533A	#RB 42D2	#RB 22B	#RB 22C2	#RB 317	#RB 46B	#RB 344	#RB 532	#RB 531	#RB 320	#RB 317A	*PG 120 5	*PG 120 6	*PG 120 3
SiO ₂	44.03	45.06	45.09	45.22	45.56	45.80	45.86	46.11	46.90	47.25	48.9	49.02	49.15	49.32
TiO ₂	2.23	3.48	2.03	2.74	2.15	2.59	2.65	2.88	4.38	3.92	3.67	3.65	3.25	3.30
Al ₂ O ₃	15.76	14.78	16.53	14.45	15.83	16.10	16.23	16.09	11.73	12.41	13.04	13.68	13.90	13.63
Fe ₂ O _{3T}	14.70	15.10	13.05	15.56	13.61	13.96	14.40	14.03	17.60	17.36	16.19	14.94	14.85	14.67
MnO	0.19	0.19	0.16	0.20	0.17	0.19	0.19	0.19	0.23	0.22	0.15	0.23	0.21	0.22
MgO	6.80	5.14	6.86	5.77	6.66	6.01	5.67	5.11	4.31	3.75	3.97	3.92	4.56	4.66
CaO	8.57	8.88	7.98	8.52	8.5	8.65	8.93	8.48	8.98	8.25	5.81	6.22	5.05	6.89
Na ₂ O	2.58	2.9	2.98	3.41	2.75	2.77	2.82	2.95	2.64	2.93	3.54	3.28	3.72	2.69
K ₂ O	1.06	0.45	1.06	0.55	0.78	0.65	0.39	0.83	1.38	1.69	0.40	1.74	1.34	1.19
P ₂ O ₅	0.35	0.66	0.34	0.45	0.38	0.49	0.49	0.54	0.59	0.67	0.70	0.61	0.58	0.57
LOI	3.4	3	3.6	2.8	3.3	2.5	2.1	2.5	1	1.3	3.3	2.4	3.0	2.5
Sum	99.67	99.64	99.68	99.67	99.69	99.71	99.73	99.71	99.74	99.75	99.67	99.69	99.61	99.64
Ba	437	312	455	326	562	390	350	491	516	631	562	826	1183	772
Rb	27.5	12.1	31.3	12.2	22.3	19.3	9.1	17.3	32.7	39.8	22.3	53.9	40.0	32.4
Sr	537.7	338.4	515.4	499.8	611.1	352.8	345.2	345.7	291.6	293.7	611.1	295.1	333.2	293.3
Zr	150.3	244.1	134.1	173.1	153.1	205.6	205.5	215.8	255	313	329.1	283.2	261.3	251.1
Nb	12.6	21.4	11.3	15.5	12.9	13.5	13.9	14.8	19.9	22.2	12.9	19.5	18.2	16.7
Zn	70	88	58	81	84	89	91	91	97	119	196	86	107	72
La	17.5	30.3	16.5	21.6	18.6	18.6	20.2	20.4	28.7	35.6	42.7	34.2	35.0	29.4
Ce	40.7	69.2	38.2	51.8	43.5	44.2	46.5	50	68.3	79.9	98.7	75.0	74.8	65.3
Pr	5.71	9.55	5.35	7.18	6.16	6.34	6.66	6.82	9.51	11	13.12	10.19	9.91	8.90
Nd	26.5	41.7	24.3	32	26.1	27.8	29.1	30.7	43.6	50.1	56.9	42.8	42.2	39.3
Sm	5.56	8.92	5.02	6.8	5.6	6.2	6.61	6.9	9.62	10.76	12.15	9.27	9.32	8.73
Eu	1.94	2.71	1.81	2.28	2.01	2.15	2.22	2.26	2.74	3.08	3.31	2.71	2.63	2.39
Gd	5.84	9.29	5.14	6.87	5.71	6.53	7.04	7.35	10.09	11.45	12.93	10.06	9.63	8.94
Tb	0.91	1.49	0.82	1.11	0.92	1.14	1.17	1.19	1.61	1.71	2.07	1.61	1.51	1.40
Dy	5.06	8.05	4.53	6.14	5.12	6.41	6.35	6.79	9.53	10.25	11.75	9.46	9.46	8.26
Ho	1	1.62	0.89	1.19	1.01	1.25	1.31	1.31	1.82	2.02	2.31	1.67	1.62	1.61
Er	2.79	4.39	2.38	3.35	2.83	3.61	3.75	3.7	4.94	5.39	6.58	4.59	4.72	4.56
Tm	0.4	0.65	0.36	0.49	0.39	0.52	0.54	0.55	0.76	0.81	0.94	0.74	0.65	0.65
Yb	2.37	4.15	2.3	3.04	2.5	3.09	3.41	3.46	4.44	5.02	5.92	4.58	4.08	3.83
Lu	0.36	0.57	0.31	0.43	0.36	0.46	0.5	0.52	0.65	0.73	0.84	0.71	0.64	0.63
Y	33.4	43	23.3	32.9	27.1	33.5	35.6	36.5	49.8	52.5	66	46.7	43.4	42.0
Ga	19.5	24.9	20.2	21.7	22.1	23.3	22.3	21.6	23.1	24.4	22.1	21.2	21.2	20.0
mg#	0.48	0.40	0.51	0.42	0.49	0.46	0.44	0.42	0.33	0.30	0.33	0.34	0.38	0.39

#: Sills; *lava flows.

account $\text{Fe}_2\text{O}_3/\text{FeO}$ equals 0.15. These values suggest an evolved basaltic magma source for these rocks, once higher values between 0.74 and 0.80 refers to primitive magma (Jaques & Green 1979, 1980, Takahari & Kushiro 1983).

Major and trace-elements variation diagrams using MgO as differentiation index (Fenner's diagrams; Figs. 11 and 12) define relative linear trends. A negative relationship is observed in the major-elements diagrams between MgO and contents of SiO_2 , TiO_2 , P_2O_5 , Fe_2O_3 and MnO, while CaO and Na_2O are randomly distributed, which suggests they were largely mobilized during post-magmatic events. K_2O yields a divergent pattern in which its content decreases and then increases again as the MgO content decreases.

Trace-elements show that concentrations of Ba, Nb, Zr, La, Ce and Y decrease as MgO content increases.

The rocks from Salto do Céu Suite have tholeiitic affinity with typical FeO_i enrichment relative to MgO taking into account nearly constant alkali values, as seen in the AFM diagram (Irvine & Baragar 1971; Fig. 13A), and are classified as sub-alkaline basalts and iron-rich tholeiitic basalts following the classification of Winchester & Floyd (1977; Fig. 13B) and Jensen (1976; Fig. 13C), respectively.

In order to unravel their tectonic settings, diagrams Zr/Y versus Zr (Pearce & Norry 1979; Fig. 13D), Zr – Nb – Y (Meschede 1986; Fig. 13E) and $\text{MgO} - \text{FeO}_i - \text{Al}_2\text{O}_3$ (Pearce *et al.* 1977; Fig. 13F) were elaborated in which the rocks

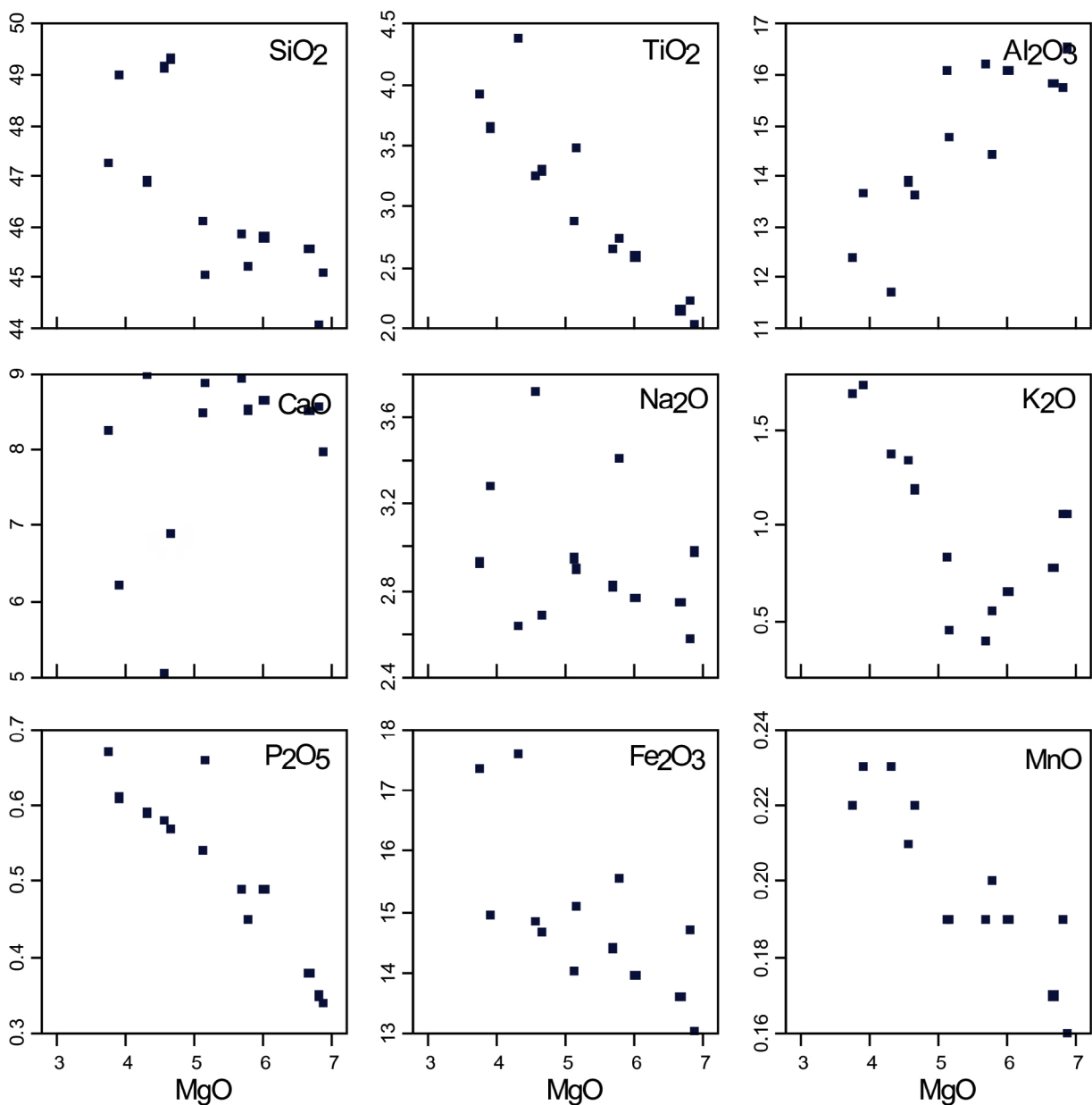


Figure 11. MgO variation diagrams versus major-elements (% weight) for rocks from Salto do Céu Suite.

from SCS overlap the domains proposed by these authors for continental intraplate basalts.

Pattern distribution of rare earth elements (REE) normalized to primitive mantle values of McDonough & Sun (1995) is illustrated in Figure 14A. Heavy REE (HREE) fractionation relative to light REE (LREE) is observed. There is a clear distinction between the two rock groups in which one of them is richer in REE, with La_N greater than 100 and a discrete negative Eu anomaly (group 1), corresponding to the rocks with lower MgO contents; the second group does not show this pattern having La_N less than 100 (group 2). There is no relation between the shape of occurrence (sills and flows) with the groups of high and low La_N .

Figure 14B shows a primitive-mantle normalized multi-element spidergram according to values of McDonough & Sun (1995). Here rocks also show a separation into two groups, where the main difference is the negative Sr anomalies for the group with La_N greater than 100, and positive Sr anomalies for the group with La_N less than 100, which corresponds to the group with discrete Eu anomaly. For other elements, both groups follow a very similar pattern with negative Rb, K, and Nb anomalies, and positive Ti anomaly likely reflecting no fractionation of Fe-Ti oxides. The negative Nb anomaly, in its turn, may be attributable to crustal assimilation processes.

DISCUSSION AND FINAL CONSIDERATIONS

Based on data from semi-detailed geological mapping as well as petrographic and lithochemical characterization, here we conclude the basic rocks from the region of Salto do Céu (Mato Grosso) occurring as sills and lava flows belong to the same magmatic event that gave rise to the Salto do Céu Suite. Moreover, the U-Pb baddeleyite age of 1439 ± 4 Ma (Teixeira *et al.* 2015), and geochronological dataset available for rocks from the Rio Branco Intrusive Suite (1427 ± 10 Ma, 1423 ± 0.2 Ma and 1423 ± 6 Ma obtained by Geraldtes *et al.* 2001, 2004, Araújo 2008; respectively) indicate that both suites are derived from a bimodal coeval magmatism.

The temporal relation of Salto do Céu (mafic rocks) and Rio Branco (felsic rocks) suites is corroborated by the presence of magma mingling diagnostic features, such as mafic microgranular enclaves with alkali feldspar xenocrysts, diffuse and transitional boundaries and hybridization zones, as previously described. Moreover, oscillatory or reverse zoning in plagioclase can result from the interaction of felsic and mafic magmas. Ginibre *et al.* (2002) described zoning patterns in plagioclase crystals of the Parinacota Volcano (Chile) and assumed that this features can be generated by a magma chamber recharge with mafic magma.

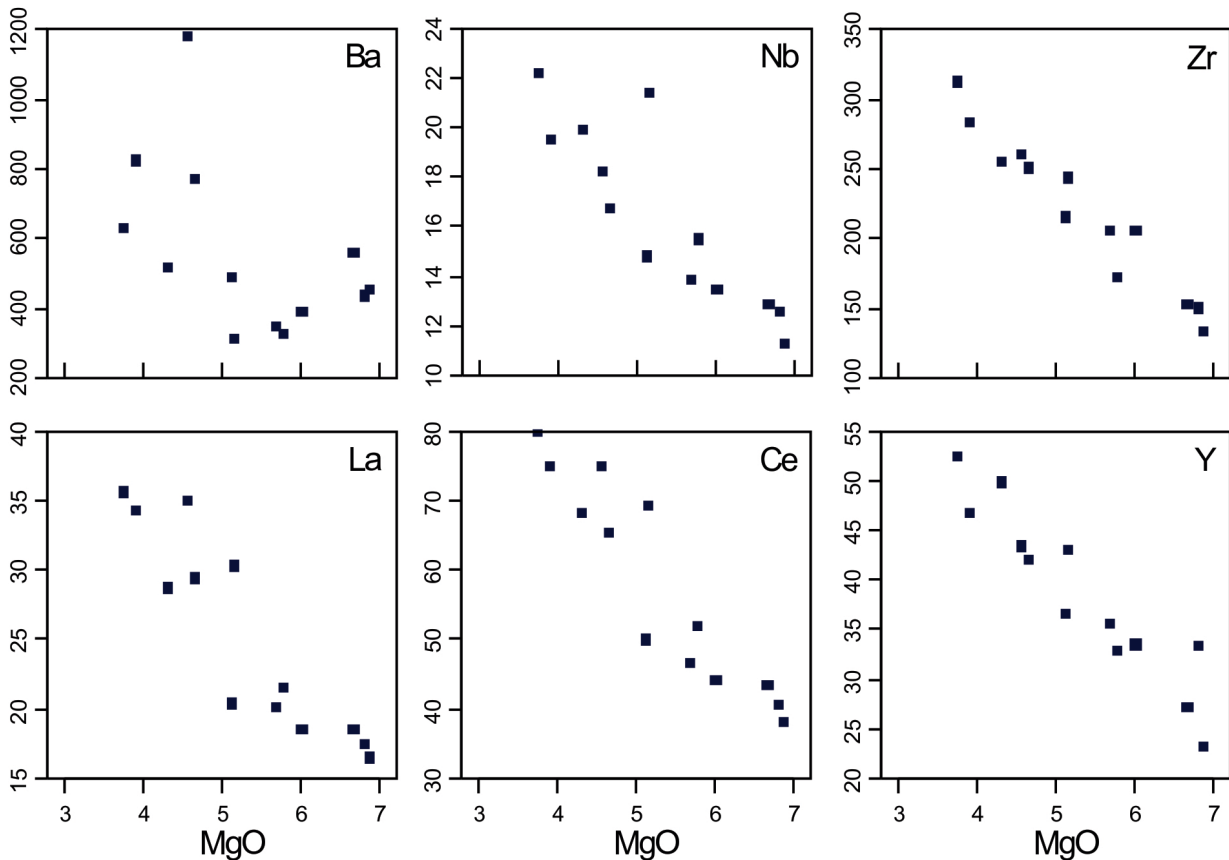
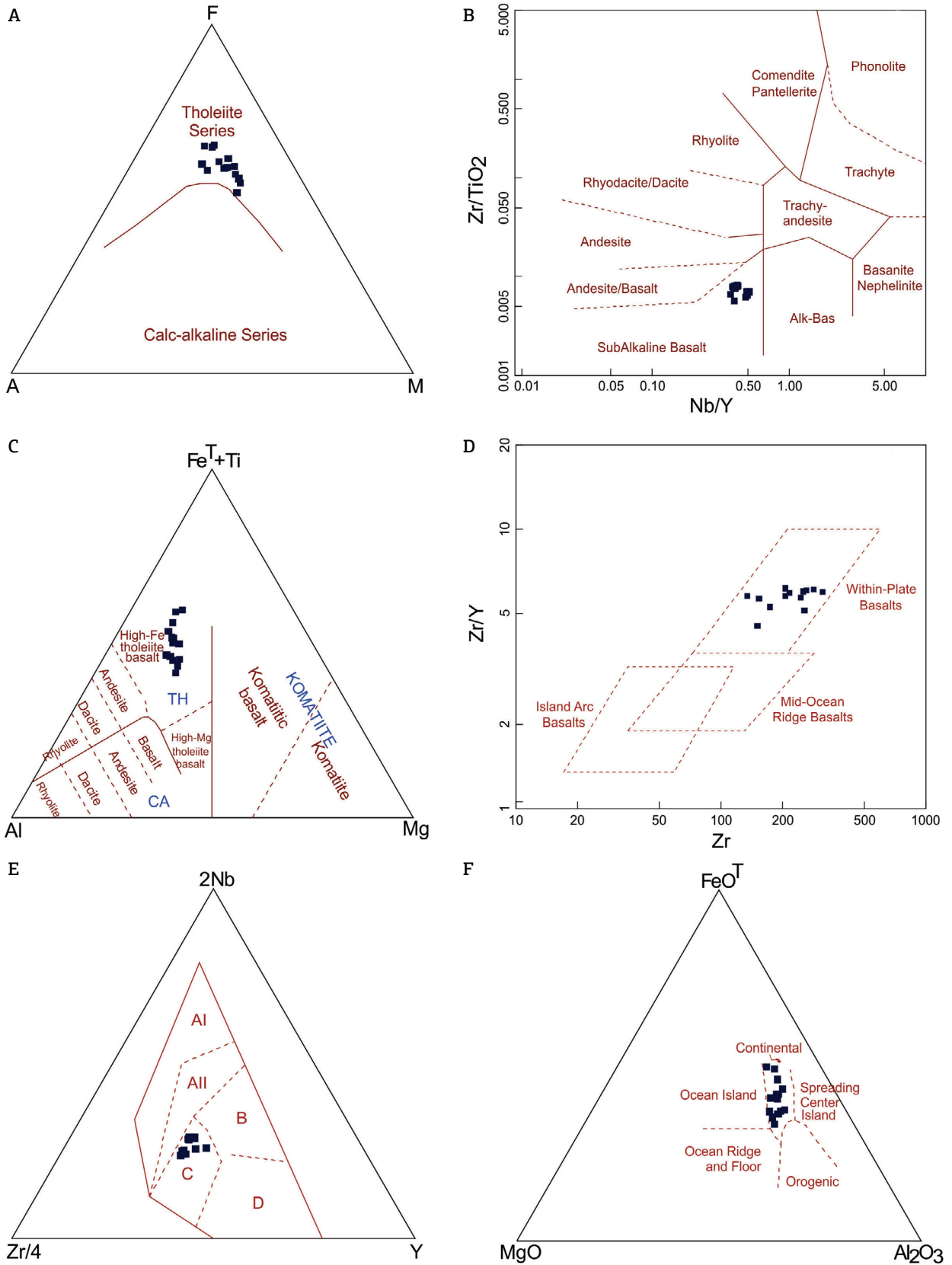


Figure 12. MgO variation diagrams (% weight) versus trace-elements (ppm) for rocks from Salto do Céu Suite.



AI-AII: Within-Plate Alkaline Basalts; AII-C: Within-Plate Tholeiites; B: P-type Mid-Ocean Ridge Basalts; D: N-type Mid-Ocean Ridge Basalts; C-D: Volcanic Arc Basalt.

Figure 13. Classification diagrams for rocks from Salto do Céu Suite: (A) Irvine & Baragar (1971); (B) Winchester & Floyd (1977); (C) Jensen (1976); (D) Pearce & Norry, (1979); (E) Meschede (1986); (F) Pearce et al. (1977).

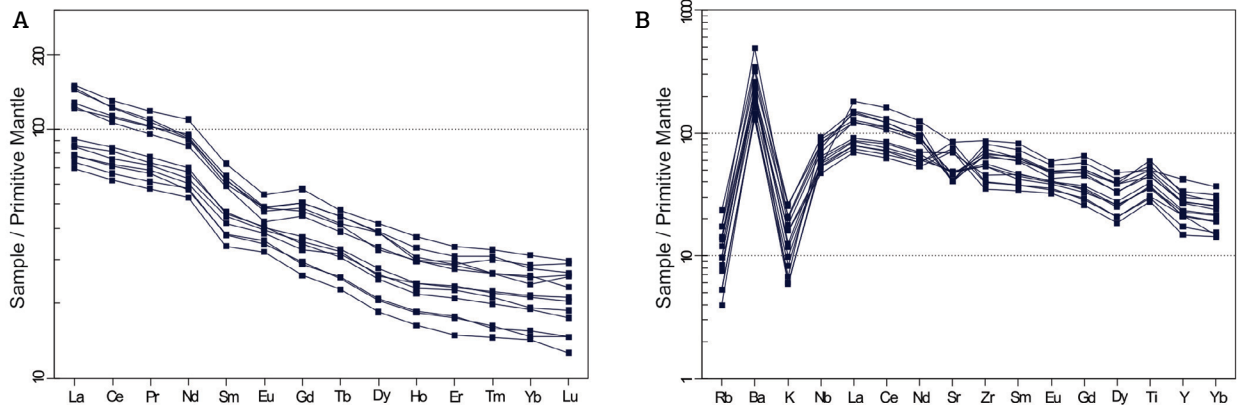


Figure 14. Rare earth elements (REE) (A) and multi-element spidergrams (B) normalized to primitive values of McDonough & Sun (1995) for rocks from Salto do Céu Suite.

The TIMS U-Pb baddeleyite ages of 1110 ± 2 Ma and 1112 ± 2 Ma measured by Teixeira *et al.* (2015) for the mafic sills from Rincon del Tigre, respectively, in Bolivia and Huanchaca as well as that U-Pb baddeleyite age of 1439 ± 4 Ma obtained by Teixeira *et al.* (2016) for the basic magmatism of the Salto do Céu Suite, in Brazil, show that they are not related to a single igneous-tectonic event attributable to an older crustal extension episode that resulted in mantellic magma ascent, opposing previous proposals of Ruiz *et al.* (2010a), Lima *et al.* (2012), among others.

Geochronological data made available by Leite & Saes (2003), Santos *et al.* (2005) and Geraldés *et al.* (2014) point out that the sedimentary cover hosting sills and lava flows of the Salto do Céu Suite is not attributable to the defined Aguapeí Group of the type-area in Santa Barbara Hill (Souza & Hildred 1980).

The diagenesis of Fortuna Formation, basal unit of Aguapeí Group, occurred between 1165 ± 27 Ma and 1149 ± 7 Ma based on SHRIMP U-Pb dating of diagenetic xenotime from Santa Barbara Hill (Santos *et al.* 2005). A maximum deposition age of 1.3 Ga on detrital zircons is attributed to it according to Leite & Saes (2003; bottom of Aguapeí Group in São Vicente and Lavrinha hills) and Geraldés *et al.* (2014; Fortuna Formation in Ricardo Franco and Santa Barbara hills). The younger basement rocks of this group in the surrounding region are the post-kinematic granites of the Pensamiento Suite dated at 1290 Ma by U-Pb (LA-IPC-MS) (Jesus *et al.* 2010).

Geraldés *et al.* (2014) report a maximum deposition age around 1540 Ma (U-Pb, LA-IPC-MS) for this group in the

Rio Branco Hill, which supports the notion that it is a different sedimentary cover, likely another stratigraphic unit deposited in the Calymmian once the younger rocks of the underlying basement consist of post-kinematic granites of the Alvorada Suite dated around 1440 Ma by U-Pb (TIMS) on zircon (Geraldés *et al.* 2001, Ruiz 2005).

The mafic-ultramafic suites named Figueira Branca and Indivaí (1.42 a 1.41 Ga; Teixeira *et al.* 2011) are part of the Jauru Terrane and are chrono-correlated to the Salto do Céu and Rio Branco suites as well as may be derived from a single magmatic event.

The mafic sills and lava flows from Salto do Céu Suite and the rocks from Rio Branco Suite are here interpreted as an anorogenic bimodal suite formed in intraplate settings, in extensive tectonic regime, which may reflect an important tectonic milestone associated with the breakup of the Columbia (Nuna) Supercontinent.

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