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Timing of granitic magmatism in the northern Borborema Province, Brazil: a U–Pb study of granitoids from the Alto Pajeú Terrain

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Abstract

The Alto Pajeú Terrain (APT) is a SW–NE trending fold belt in the Neoproterozoic Borborema Province (NE Brazil), formed by metasedimentary sequences interlayered with metavolcanosedimentary units, both intruded by granitic rocks of different compositions and ages. The tectonic evolution of the APT involves Mesoproterozoic and Neoproterozoic transtensional and contractional tectonic events. In this study, we present U–Pb zircon ages of five granitoids selected according to a generally accepted relative chronology: (a) the Tuparetama granite and Tuparetama migmatitic granite with low angle gneissic foliation represent syn-tangential rocks presumably related to a Transamazonian event; (b) the Amparo granite with high angle gneissic foliation related to the Brazilian/Pan-African event; and (c) the Tabira and Jabitacá post-strike-slip granites. The results obtained do not confirm the generally accepted chronology of events. Granites previously classified in different groups (Tuparetama, Amparo, and Jabitacá) belong to the same orogenic cycle (Brazilian). Large batholiths, previously suspected to have been emplaced after the strike-slip deformation, represent older crustal remnants within them. In each case they consist of particular rock types — an alkaline high-temperature granite (Tabira) and a 'granulite' (Tuparetama migmatitic granite). These older ages imply that pre-Brazilian crust-forming events such as the Transamazonian Orogeny (Tuparetama migmatitic granite estimated at ca. 2050 Ma) and Cariris Velhos event (Tabira granite at ca. 972 Ma) occurred in the APT, and their records survived the intense recycling which characterizes the Brazilian/Pan-African orogeny. © 2000 Elsevier Science Ltd. All rights reserved.

Resúmen

O Terreno Alto Pajeú corresponde a um cinturão dobrado de idade neoproterozóica, situado na Província Borborema (NE Brasil), formado por seqüências metassedimentares e unidades metavulcanossedimentares intercaladas, ambas intrudidas por rochas graníticas. Sua evolução tectônica envolve eventos transtensionais e contracionais de idade meso a neoproterozóica. No presente trabalho apresentamos idades U–Pb em zircões de 5 corpos granitóides selecionados de acordo com uma cronologia relativa comumente aceita para a região: (a) o granito Tuparetama e o granito migmatítico Tuparetama que apresentam foliação gnáissica de baixo ângulo representam rochas sin-tangenciais possivelmente relacionadas a evento Transamazônico; (b) o granito Amparo que apresenta foliação de alto ângulo, representa um *sheet* transcorrente e estaria relacionado com o ciclo Brasiliano e (c) os granitos Tabira e Jabitacá, que apresentam pouca ou nenhuma deformação, seriam granitos pós-transcorrência. Os resultados obtidos não confirmam essa cronologia de eventos. Granitos previamente classificados em grupos diferentes (Tuparetama, Amparo e Jabitacá) apresentam idades que indicam posicionamento em um mesmo ciclo orogenético (Brasiliano). Por outro lado, grandes batólitos, anteriormente considerados como tendo sido posicionados após a deformação transcorrente, tais como o granito Tabira e o granito migmatítico Tuparetama representam remanescentes crustais mais antigos. Essas idades mais antigas mostram que ocorreram no Terreno Alto Pajeú eventos de formação de crosta pré-Brasilianos, tais como os ciclos orogênicos Transamazônico (granito migmatítico Tuparetama com ca. 2050 Ma) e Cariris Velhos (granito Tabira com 972 Ma), e seus registros sobreviveram as intensas modificações que caracterizam o ciclo Brasiliano/Pan-Africano. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: U–Pb study; Granitoides; Alto Pajeú Terrain

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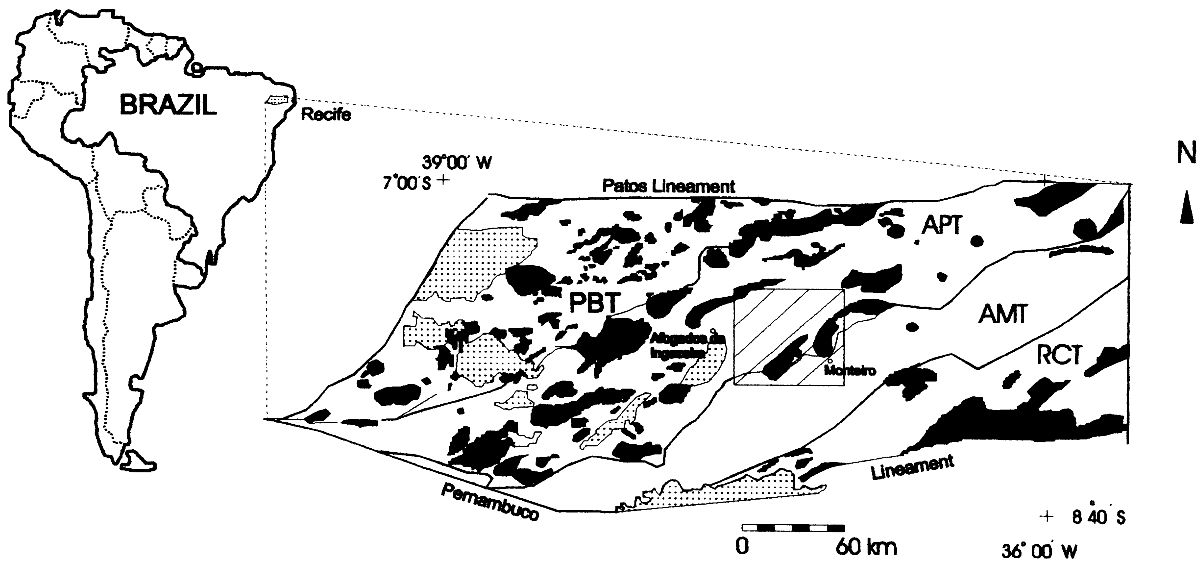

Fig. 1. Location map of the Monteiro sheet, showing the granitoids and metamorphic terrains studied (modified after Santos and Medeiros, 1997). APT: Alto Pajeú Terrain; AMT: Alto Moxotó Terrain; PBT: Piancó-Alto Brígida Terrain; RCT: Rio Capibaribe Terrain; stippled areas: Phanerozoic cover; black areas: granitoids.

1. Introduction

The Alto Pajeú Terrain (APT) is a SW–NE trending fold belt, located in the Neoproterozoic Borborema Province (NE Brazil). It extends from the Floresta area in the State of Pernambuco to the Phanerozoic coastal basins. It is limited to the north by the Patos lineament, to the south by the Alto Moxotó Terrain, and to the northwest by the Piancó-Alto Brígida Terrain (Fig. 1). The APT, together with the Alto Moxotó and Piancó-Alto Brígida Terrains, were proposed by Santos (1996) as a division of the Central Structural Domain (CSD) located between the Patos and Pernambuco lineaments. The tectonic evolution of the APT involves Mesoproterozoic and Neoproterozoic transtensional and contractional tectonic events. The APT is formed mainly by metasedimentary sequences, with minor metavolcanosedimentary units, both intruded by granitic rocks. The purpose of this study is to present new geochronological data from granitoids belonging to the APT, in order to contribute to a better understanding of its tectonic evolution, as well as that of the Borborema Province as a whole. The aforementioned granitoids were chronologically positioned using structural field criteria (Wanderley, 1990). Therefore, the data presented test the validity of such well established criteria in the regional literature.

The data presented here were obtained using the U–Pb zircon dating method. The sampling was guided by the previously proposed chronology (Wanderley, 1990). The interpretation of the ages was carefully controlled by a SEM study of the internal structures observed in the zircons and related to observed petrographic textures and structural field evidence. The same method was applied to sphene when present in the mineral assemblage.

2. Local geology

The APT in the Monteiro area consists of high-grade supracrustal (metasedimentary and metavolcanosedimentary) rocks underlain discordantly by a gneissic–migmatitic basement, both of which were intruded by several granitic bodies of different ages and compositions (Fig. 2). These rocks underwent at least three ductile deformational events with associated metamorphism.

2.1. Basement rocks

The basement comprises gneissic–migmatitic rocks in which tonalitic–dioritic to granitic–granodioritic orthogneiss belts can be distinguished. Tonalites and diorites occur as restricted belts and are essentially formed by gray, medium-grained, monzodioritic orthogneisses showing well-developed banding and migmatization. The paleosome is composed of biotite, hornblende, and feldspar, whereas the leucosome is essentially quartz-feldspathic in composition. The most common migmatitic structure is of the schlieren type. The granite-granodioritic orthogneisses have a more widespread distribution and are characterized by a well-defined compositional banding, in which quartz-feldspathic leucosome veins alternate with a melanosome composed of biotite and/or hornblende. The most common migmatitic structures are of the stromatic, schlieren, and nebulitic types.

2.2. Supracrustals

According to Wanderley (1990), the APT supracrustal rocks that crop out in the Monteiro map area and vicinity were defined as belonging to the Irajaí and Sertânia Complexes. Leite (1997) suggested that these two

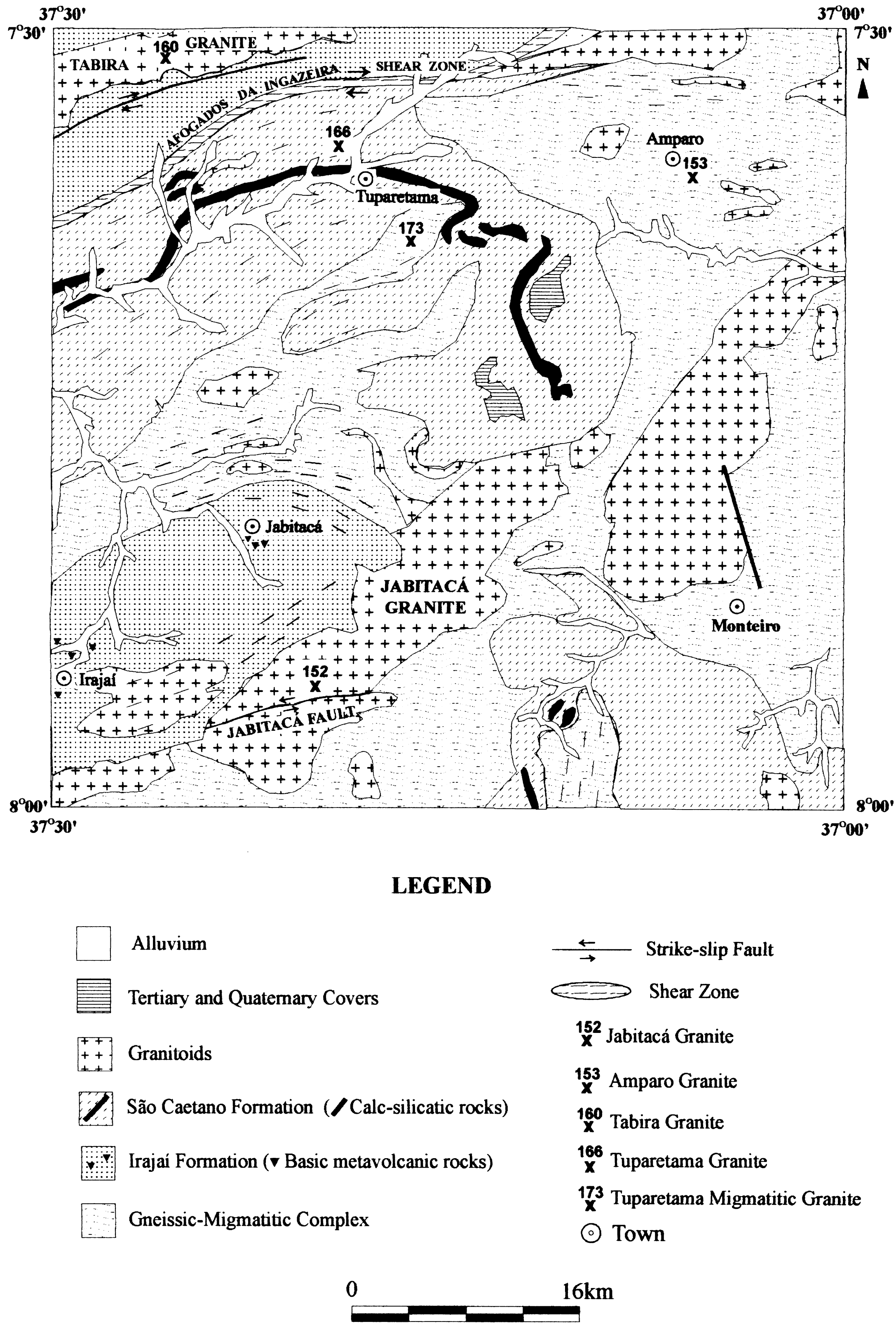

Fig. 2. Geologic sketch map of Monteiro sheet (modified after Wanderley, 1990), giving sample location numbers.

complexes should be included in the Sertânia Group, comprising the Irajaí Formation (Irajaí Complex of Wanderley, 1990), which is dominated by metavolcanosedimentary rocks, and the São Caetano Formation (São Caetano sequence of Santos, 1995), which is composed mainly of metassedimentary rocks. This classification is used in the present work.

2.2.1. Irajaí Formation

The rocks of the Irajaí Formation belong to a metavolcanosedimentary sequence in which a garnet-mica gneiss predominates, with intercalations of para-amphibolites, calc-silicate gneisses and, less frequently, marbles, metavolcanic and metaplutonic rocks such as amphibolites, metatuffs, metacherts, and metagabbros. Muscovite–biotite gneisses show a gently dipping mylonitic foliation as the main structural feature, which truncates a previous gneissic foliation defined by mica lamellae. and a compositional banding that is characterized by the alternation of felsic layers composed of plagioclase and quartz and mafic layers predominantly composed of biotite. Migmatization is locally observed. The volcanogenic component is represented by orthoamphibolite, metacherts, basic metatuffs, and metaultramafics, which crop out in a restricted area in the vicinity of Irajaí, Jabitacá, and Riacho do Meio (southwestern, central, and northeastern parts of the studied area, respectively; Fig. 2). Metagabbros occur as small metric dykes and sills.

2.2.2. São Caetano Formation.

The São Caetano Formation (Sertânia Complex, Wanderley, 1990) comprises a monotonous metasedimentary sequence that includes garnet-biotite gneisses, varying locally to biotite schists and metagraywackes, frequently migmatized, interlayered with marbles, calc-silicate gneisses and, less frequent, para-amphibolites. This formation differs from the Irajaí Formation in the large volume of interlayered calc-silicatic gneisses and the absence of mafic and ultramafic metavolcanic rocks. Otherwise, the gneissic rocks from both the Irajaí and São Caetano Formations are petrographically very similar. Biotite gneisses and interlayered calc-silicatic gneisses are the main lithotypes. The biotite gneisses show a fine to coarse grain size, gray color, and a mineral assemblage including quartz, plagioclase, biotite, garnet ± sillimanite and tourmaline. The calc-silicatic rocks vary in thickness from a few centimeters to meters and reach several kilometers in length. Their mineralogy includes diopside, microcline, plagioclase, quartz, calcite, hornblende, epidote, sphene, biotite, and minor accessory phases. They show either massive or banded structure.

2.3. Granitoids

In the study area, granitoids consist of granodioritic to quartz-monzogranitic orthogneisses, syenitic granites, granites, quartz-syenites, and diorites. They were previously classified by Wanderley (1990) according to their field relationships to the main tectonic event (Fig. 2). The syn-tangential granitoids are characterized by structures related to several deformational events. They show a pronounced gneissic banding and are concordant to sub-concordant to the country rocks. The main characteristic of the syn-transcurrent granitoids is their sheet-like form, which is associated with a steeply dipping gneissic foliation. The post-to late-transcurrent granites form elongated batholithic bodies parallel to the regional structural trend. They show little or no deformation. The magmatic activity also includes felsic and mafic discordant dykes. The felsic dykes are of granitic composition, fine grained, and gray to pink in color; their mineral assemblage includes quartz, feldspar, and biotite. The mafic dykes are very fine grained and dark in color; their mineral assemblage includes quartz, feldspar, and amphibole.

2.4. Metamorphism and deformation

Three ductile deformation events were observed in the APT. The older event (D_0) is responsible for the development of the gneissic banding (S_n) in the basement orthogneisses. The D_1/D_2 deformation corresponds to a low-angle tangential tectonic event that affected both the basement and supracrustal rocks and was partially responsible for the present geometric framework of the area. The D_3 deformation is related to localized ductile shear zones with associated open folds overprinting the structures formed during D_1/D_2. The observed mineral assemblages and a thermobarometric study in metapelitic and orthoamphibolitic rocks showed that the metamorphism related to the D_1/D_2 deformation corresponds to amphibolite/high-amphibolite facies conditions, with temperatures and pressures in the range 600–680°C and 6.0–7.5 kbar, respectively (Leite, 1997).

3. Previous geochronological data

The oldest geochronological data available for the CSD (Brito Neves, 1975; Santos and Brito Neves, 1984) were obtained using the Sm–Nd and Rb–Sr methods, they revealed the role of the Transamazonian and Brazilian cycles as the main crust-forming events, although some ages already suggested the occurrence of intermediate events. Recently, new data support a third main crust-forming episode, the Cariris Velhos event, and arguments were developed about the polycyclic evolution of some fold belts in the Borborema Province (Jardim de Sá, 1994).

Brito Neves et al. (1990) published Rb–Sr whole-rock isochrons and U–Pb zircon ages from felsic metavolcanic rocks occurring in the Piancó-Alto Brígida Fold Belt. U–Pb data from distinct metavolcanic rocks but belonging to the same metavolcanosedimentary sequence, when considered together, provide an upper intercept age of 1117 ± 83 Ma and a lower intercept of 457 ± 81 Ma. The upper intercept age was interpreted as representing the zircon crystallization age and, consequently, the age of the volcanic rocks. A Rb–Sr

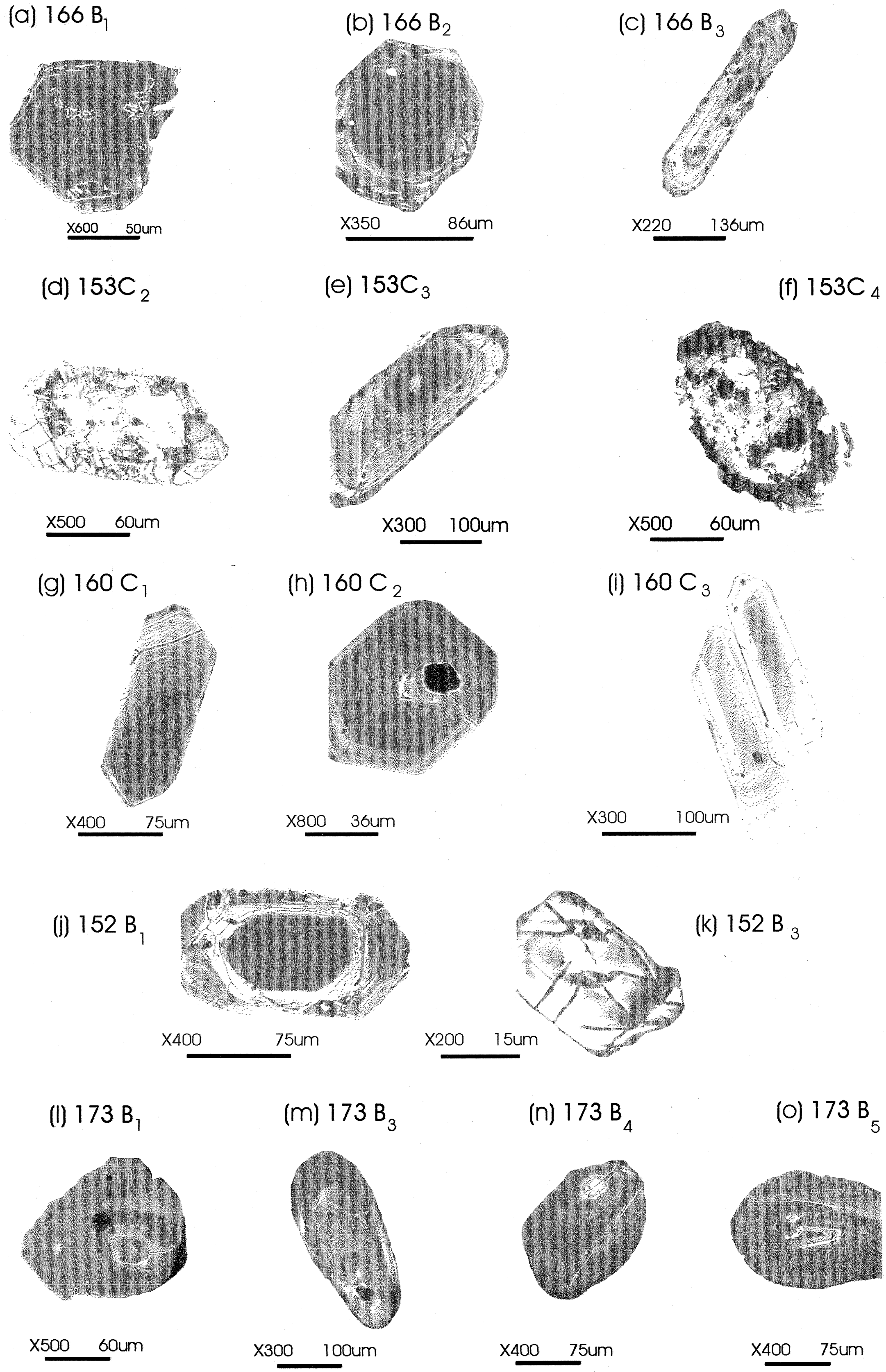

Fig. 3. Scanning electron microprobe backscattered electron images of selected zircons from the granitoids (see Fig. 2 for sample locations). Key: **a**, **b**, **d**, **f** and **j** show inherited core; **e** shows a small inherited core; **c**, **g**, **h** and **i** show zoning from the center to the border; **l**, **m**, **n** and **o** show round form and zoning not centered with respect to the crystal outline.

age of 950 ± 7 Ma was interpreted as the result of metamorphic resetting. These results, as well as previous data from the literature (Brito Neves et al., 1984; Jardim de Sá et al., 1988; Lima et al., 1986), led Brito Neves et al. (1990) to point out a crust-forming event dated at 1200–900 Ma — the Cariris Velhos event.

Ages of orthogneisses from the CSD are quoted by Jardim de Sá (1994) in the Afrânio and São José do Egito areas, State of Pernambuco. Rb–Sr isochrons (968 ± 35 Ma and 968 ± 14 Ma, Afrânio area), ^{207}Pb–^{206}Pb zircon evaporation ages (1039 ± 25 Ma and 927 ± 25 Ma, São José do Egito area), and a U–Pb zircon age of 986 ± 48 Ma (Afrânio area) all belong to the Cariris Velhos event. Studying granitoids of the Seridó Fold Belt, Leterrier et al. (1994) found zircon U–Pb ages of ca. 579 Ma, interpreted as the peak of the thermal manifestations related to the Brazilian orogeny. Using U–Pb and Sm–Nd isotopic data, Santos (1995) suggested an accretion/collision tectonic regime for the evolution of the Borborema Province from the end of the Mesoproterozoic to the Neoproterozoic, emphasizing the 1.1–1.0 Ga Cariris Velhos event and the 750–570 Ma Brazilian Orogeny. Van Schmus et al. (1995) applied the U–Pb and Sm–Nd isotope methods to volcanic rocks in the eastern part of the Borborema Province. Their results indicated that Brazilian Orogeny was a major crust-forming event but also showed the presence of a 1000–900 Ma event. Using U–Pb geochronology and depleted mantle model ages, Kozuch et al. (1997) confirmed the magmatic activity that occurred from 1000 to 750 Ma in the CSD. Recently, Corsini et al. (1998) studied magmatic and metamorphic rocks of the Borborema Province (Patos region, Paraíba State), utilizing the $^{40}Ar/^{39}Ar$ method (step-heating technique) for amphibole, muscovite, and biotite. They observed well-defined ages peaks of ca. 540 Ma for amphiboles and ca. 502 Ma for muscovites.

4. Analytical procedures

Mineral separation, zircon selection and physical preparation, chemical dissolution, and isotopic analyses were carried out at the laboratories of Centre de Recherches Pétrographiques et Géochimiques (CRPG/CNRS), Vandoeuvre-lés-Nancy, France. The procedure used was a modified version of that proposed by Heaman and Parrish (1991).

After crushing, heavy minerals were separated using the vibrating table and/or gold-pan, heavy liquids, magnetic separator, and handpicking. Most of the analyzed fractions were non-magnetic at 0°/3.0 Å. During handpicking, the main criterion used for selecting the fractions was crystal morphology. For the Amparo and Tabira samples, zircon typological classification (Pupin, 1980) was also used, in order to obtain the most homogeneous zircon fractions. Representative SEM images of each analyzed zircon fraction are shown in Fig. 3.

The weight of the analyzed fractions varied from 0.03 to 0.6 mg, although the majority weighed about 0.1 mg. To minimize Pb loss due to post-crystallization thermotectonic events, the zircon crystals were abraded using Krogh's technique (Krogh, 1982). Abrasion is especially important in clearly magmatic zircons, in order to get data as close as possible to the concordia.

Before chemical dissolution, each fraction was washed with hot 3N HNO_3, distilled water, and distilled acetone. Dissolution was carried out in teflon capsules, using concentrated HF at 240°C (Parrish et al., 1987) for 30 h, followed by 3 N HCl at 180°C for 14 h. Two aliquots were separated before elution on anion exchange resin acidified with HCl (Krogh, 1973), one of which was spiked with a mixed ^{235}U–^{208}Pb tracer. The samples were prepared using silica gel and phosphoric acid and were mounted on a rhenium filament. U was analyzed as UO_2. Eight batches, including seven zircon fractions and one blank, were analyzed. The Pb procedural blanks yielded from 33 to 142 pg (most in the 33–60 pg range). Errors are given at the 2 sigma level; they take into consideration measurement uncertainties, common Pb and procedural Pb blank, and mass discrimination, and were corrected according to the model of Stacey and Kramers (1975). Regression lines were calculated and drawn using the Isoplot software (Ludwig, 1985) adapted to the Macintosh computer system by Nemchin et al. (1994). To calculate the regression lines, $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ analytical errors were fixed at 1% in three samples (153, 166, and 173), even though the analytical errors were always lower than that. Table 1 presents the analytical data for the studied samples.

5. Sample description and geochronological results

5.1. Tuparetama granite (Sample 166)

The Tuparetama granite, located northwest of the city of Tuparetama (Fig. 2), is a sheet-like body within the biotite-gneisses of the São Caetano Formation. It is a gray, fine-grained granite with weakly developed foliation and compositional banding that dips gently NW (~20°). It shows a stretching mineral lineation (quartz) as well as mafic enclaves (biotite rich), parallel to the main foliation. Quartz, plagioclase, biotite, and microcline form the main mineral assemblage. Accessory minerals include epidote, allanite, zircon and apatite.

Three zircon fractions, with grain size greater than 100 μm, were analyzed. The B_1 fraction is formed by light brown short euhedral crystals; the B_2 fraction corresponds to light brown rod-like prismatic crystals; the B_3 fraction is formed of colorless to light brown needle-like crystals. On SEM images (Fig. 3), the B_1 and B_2 fractions crystals show homogeneous cores (inherited cores) and zoned borders; the B_3 fraction crystals do not show any indication of inherited cores, presenting a regular zoning from center to rim.

Table 1
U–Pb isotopic data for granites of the Monteiro Area

Granite	Fraction	Weight (mg)	Pb (ppm)	Total U (ppm)	Atomic ratios				Ages (Ma)		
					$^{206}Pb/^{204}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
Tuparetama (166)	B1	0.08	92	456	1683	0.14704	2.0818	0.10268	884	1143	1673
	B2	0.09	86	425	3782	0.16296	2.4282	0.10807	973	1251	1766
	B3	0.03	101	1002	809	0.09125	0.7655	0.06085	563	577	634
Amparo (153)	C2	0.17	78	432	4563	0.16669	2.8622	0.12454	994	1372	2023
	C3	0.16	45	458	477	0.09152	0.7807	0.06187	564	586	670
	C4	0.08	83	702	2580	0.11024	1.3300	0.08750	674	859	1372
Jabitaca (152)	B1	0.01	112	43	59	0.13412	1.4262	0.07712	811	900	1124
	B3	0.03	66	179	262	0.07675	0.6458	0.06103	477	506	640
	Spha[a]	0.85	84	166	402	0.04535	0.3786	0.06056	286	326	624
Tabira (160)	C2	0.03	97	649	885	0.14290	1.3908	0.07059	861	885	946
	C1	0.06	56	363	1,331	0.14610	1.4263	0.07081	879	900	952
	C4	0.08	87	520	964	0.15968	1.5700	0.07131	955	958	966
	Sph[a]	0.44	20	216	447	0.09860	0.8187	0.06023	606	607	612
Tuparetama Migmatitic (173)	B1	0.66	84	250	24,214	0.32401	5.4507	0.12200	1809	1893	1986
	B3	0.59	86	245	11,704	0.33599	5.7499	0.12411	1867	1939	2017
	B4	0.51	90	256	10,278	0.33745	5.7568	0.12373	1874	194	201
	B5	0.53	100	300	4871	0.31949	5.4133	0.12289	1787	1887	1998
	B6	0.41	89	255	7910	0.33622	5.7645	0.12435	1868	1941	2018

[a] Sph: sphene fraction.

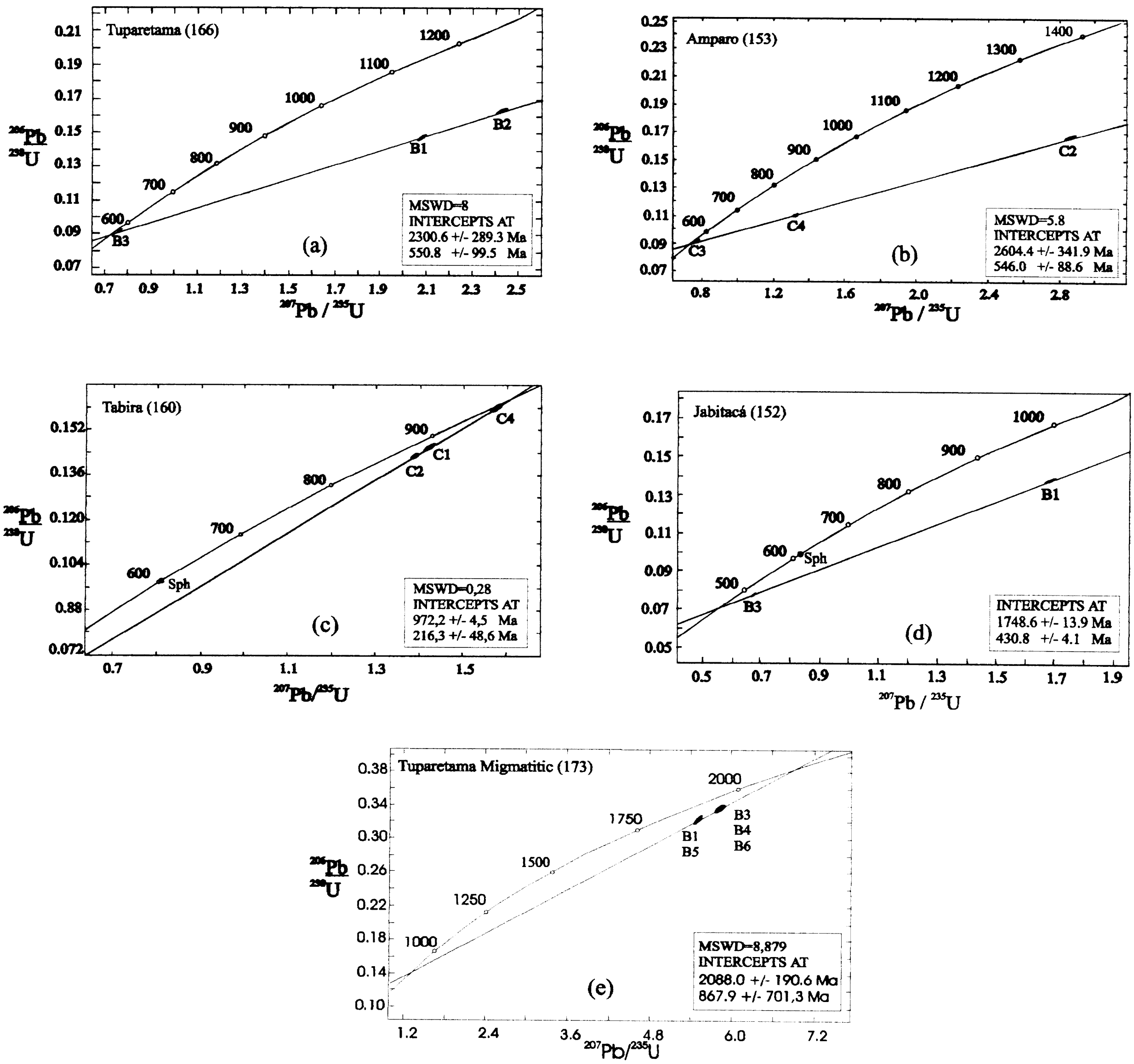

Fig. 4. Concordia diagrams (see Fig. 2 for sample locations): (a) Tuparetama Granite (166); (b) Amparo Granite (153); (c) Tabira Granite (160); (d) Jabitacá Granite (152); (e) Tuparetama Migmatitic Granite (173).

On the concordia diagram (Fig. 4a), the regression line was calculated with errors normalized at 1% to improve the poor alignment of the analytical points. It yielded a discordia (MSWD = 8) with a lower intercept at 551 ± 99 Ma and an upper intercept at 2300 ± 289 Ma. The high degree of discordance for the B_1 and B_2 fractions is explained by the presence of inherited cores. The B_3 fraction plots close to the lower intercept; its regular zoning and lack of inherited core suggest a syn-magmatic crystallization.

The poorly defined upper intercept is probably meaningless but confirms the high level of inheritance in this granite, as already foreseen due to the abundance of observed cores. In any case, the results indicate that the granite is of Neoproterozoic age, but a precise age cannot be defined at this point.

5.2. Amparo granite (Sample 153)

The Amparo granite corresponds to one of several granitic sheets that occur concordantly in the gneiss-migmatitic complex, in the vicinity of Amparo, Paraíba State (Fig. 2). It is a fine- to medium-grained rock with banding and foliation partially developed. The mineral assemblage consists of quartz, plagioclase, K-feldspar, and biotite. Accessory minerals include epidote, allanite, and zircon; secondary minerals are sericite, calcite, white mica, and chlorite.

Three zircon fractions, with grain size varying from 75 to 100 μm, were analyzed. The C_2 fraction corresponds to light brown elongated tabular crystals; the C_3 fraction is formed by light brown to colorless elongated prismatic crystals with equidimensional prismatic faces; and the C_4 fraction is composed of light brown to colorless short crystals. SEM images of the C_2 and C_4 fraction crystals show inherited cores that are rimmed by zoned borders with variable thickness. The C_3 fraction crystals show a regular zoning from center to rim, but a differentiated core was observed in some crystals (Fig. 3).

On the concordia diagram (Fig. 4b), the regression line was calculated with 1% analytical error because of the poor alignment (MSWD = 5.8). The C_2 and C_4 fractions are highly discordant as a consequence of inherited cores. In contrast, the C_3 fraction is characterized by presumably magmatic crystals. This fraction plots close to the lower intercept. Therefore, the lower intercept age (546 ± 88 Ma) is interpreted as a minimum emplacement age for the Amparo granite. Regarding the upper intercept, one can apply the same reasoning as discussed for the Tuparetama granite.

There is thus no obvious difference in the U–Pb systematics of the two granites, notwithstanding the fact that one of them (Tuparetama) was considered as an old syn-tangential intrusive whereas the other (Amparo) was believed to have been emplaced during a Brazilian strike-slip event. From our results, the two granites appear to belong to the Brazilian Orogeny, but their relative chronology was not precisely determined.

5.3. *Tabira granite (Sample 160)*

The Tabira granite, located in the NW corner of the Monteiro sheet (Fig. 2), has batholithic dimensions, elongated SW–NE and extending from São José do Egito (not shown on Fig. 2) to Tabira. Two different rock types occur within the pluton, which show contact relationships and features that suggest two distinct magmatic events. The more deformed rock type, which occurs locally, was analyzed for this work. It is a coarse-grained granite composed of quartz, K-feldspar, plagioclase, amphibole, and biotite as the main mineral assemblage, and epidote, allanite, zircon, apatite, and garnet as accessory minerals. Plagioclase and K-feldspar crystals are strongly stretched parallel to an E–W sub-vertical foliation. The less deformed rock type shows the same mineralogical composition but higher biotite/amphibole and plagioclase/K-feldspar ratios.

The analyzed sample contains good quality zircons. They are light brown to colorless crystals, showing an excellent transparency and almost devoid of fractures or inclusions. Three fractions, with granulometry varying from 75 to 100 μm, were analyzed. The C_1 fraction is formed by elongated crystals; the C_2 fraction is formed by short and non-tabular crystals, and the C_4 fraction includes crystals similar to those of the C_1 fraction, the only difference being the tabular habit. SEM images for all three fractions show crystals with regular zoning from center to rim, which are interpreted as typically magmatic (Fig. 3).

The concordia diagram (Fig. 4c) shows a well-aligned discordia (MSWD = 0.28). The upper intercept, controlled by a sub-concordant point (C_4), yielded an age of 972–5 Ma, interpreted as the emplacement age of the granite. The lower intercept (216 ± 50 Ma) has no precise geologic meaning but suggests that the lead loss, indicated by the discordant fractions, may result from a younger tectonic event. In order to test this possibility, a sphene fraction was analyzed and yielded a concordant age of 612 ± 9 Ma. This age corresponds to a metamorphic event associated with the Brazilian Orogeny.

5.4. *Jabitacá granite (Sample 152)*

The Jabitacá granite, of batholithic dimensions (30 × 6 km), occurs in the central part of the Monteiro map area and trends SW–NE (Fig. 2), intruding basement gneisses, migmatites, and muscovite-biotite-gneisses of the Irajaí Formation. It is a homogeneous granite composed of quartz, plagioclase, microcline, and biotite as the main mineral assemblage, with epidote, allanite, sphene, zircon, apatite, and opaque minerals as accessory minerals. The secondary assemblage includes sericite, chlorite, epidote, and calcite. The granite shows phaneritic and inequigranular texture, fine to medium grain size, with plagioclase phenocrysts in a matrix formed by quartz, microcline, and interstitial biotite. Deformed quartz crystals showing wave extinction are the main post-crystallization deformational feature observed. Biotite and secondary muscovite lamellae around plagioclase phenocrysts are also observed, which may be the result of shearing related to the Jabitacá fault that cuts the granitic batholith.

As the zircon yield was very small, only two fractions were analyzed, and one was too small to be measured accurately on the mass spectrometer; thus, a sphene fraction was added to try to constrain the poorly defined lower intercept. The zircon fractions analyzed were non-magnetic with a grain size varying from 100 to 150 μ. The B_1 fraction was composed of short, tabular, automorphic, light brown to colorless crystals; the B_3 fraction was composed of light brown to colorless crystals that were free of inclusions. SEM images show an inherited core and zoned rim for the B_1 fraction, but no inherited core was observed for the B_3 fraction (Fig. 3).

On the concordia diagram (Fig. 4d), the given values for the intercepts are only indicative, since the regression line was constructed using only two zircon fractions. However, the lower intercept is controlled by the B_3 fraction, which was obtained from a needle crystal population. The sphene 624 ± 8 Ma age suggests that the Jabitacá granite also belongs to the Brazilian Orogeny.

5.5. *Tuparetama migmatitic granite (Sample 173)*

The Tuparetama migmatitic granite is located to southeast of Tuparetama (Fig. 2). It was described by Wanderley (1990) as a basement granitic-gneiss. It is a highly deformed and migmatized granitic rock composed mainly of quartz, plagioclase, biotite, and amphibole. It has a porphyritic texture, with plagioclase phenocrysts usually elongated according to the main foliation plane.

The majority of the zircon population in this rock shows a rounded morphology characteristic of zircons from granulitic, migmatitic, and detrital rocks. Five zircon fractions (100–150 μm) were analyzed. The B_1 fraction is composed of short, sub-rounded, light brown crystals; the B_3 fraction is composed of elongated, light brown crystals with rounded edges; the B_4 fraction is composed of short, tabular, light brown crystals with preserved faces; the B_5 fraction includes crystals similar to the B_4 fraction but with more pronounced rounded edges; the B_6 fraction is composed of light brown, elongated, euhedral crystals with preserved faces and edges. The most striking morphological features observed by SEM of these rounded crystals are the presence of zoning, which is not centered with respect to the crystal outline, and small overgrowth bands at the crystal rims (Fig. 3).

The five analyzed fraction are strongly discordant and are grouped in two separate clusters on the concordia diagram (Fig. 4e). These do not define a discordia line because, although common lead is very low, as indicated by the high $^{206}Pb/^{204}Pb$ ratios, the fractions are poorly aligned. To estimate the age of the migmatitic granite protolith, a calculation was done using 1% error on the isotopic ratios and adding as an artificial lower intercept a point at 612 Ma, the age of the Tabira sphene and assumed to represent the age of the main metamorphic disturbance. The result is an upper intercept age of 2052 ± 13 Ma (MSWD = 11) which is believed to represent a good estimate of the primary emplacement age of the granite, the age of the migmatitic event being still unknown. In any case, even if this age is only indicative, Pb isotopic data obtained on this granite confirm that preserved remnants of older plutonic rocks may remain within the high grade metamorphic rocks and associated plutonites of the Brazilian assemblages of the Borborema Province.

6. Discussion and conclusions

1. During this study, we tried to select some fractions of regularly zoned zircon of presumably magmatic origin. None of them is perfectly concordant and able to yield a very precise age. However, in adding to the study the analysis of sphene fractions, when this mineral is available, a complementary constraint may be used. Sphene $^{207}Pb/^{206}Pb$ ages of 624 ± 8 Ma (Jabitacá) and 612 ± 9 Ma (Tabira)-the former age being discordant, suggest the major event that occurred in the APT was the Brazilian Orogeny at ca. 620–630 Ma.
2. Ages obtained during this study do not confirm the preliminary relative chronology based on field observations. Tuparetama, Amparo, and Jabitacá, previously attributed to different groups, yielded similar results. The entire tectonic evolution, from the so-called tangential event to the latest strike-slip movements, belongs to the same orogenic cycle — i.e. the Brazilian Orogeny, but we did not succeed in the discrimination of the two events.
3. Older crustal remnants were identified within the large batholiths, previously suspected to have been emplaced after the transcurrent deformation. In each case, they consist of particular rock types: an alkaline high temperature granite (Tabira) and a ‘granulite’ (Tuparetama migmatitic granite). They indicate the presence of pre-Brazilian crust-forming events such as the Transamazonian event (Tuparetama migmatitic granite estimated at ca. 2050 Ma) and the Cariris Velhos event (Tabira granite at ca. 972 Ma). Similar conclusions, especially concerning the presence of a Middle Proterozoic event (the Cariris Velhos) have been obtained previously in other regions of the CSD, Borborema Province (Brito Neves et al., 1990; Jardim de Sá, 1994; Van Schmus et al., 1995; Kozuch et al., 1997).
4. The systematic presence of zircon crystals with inherited cores in Brazilian cycle granites (Tuparetama, Amparo, Jabitacá) suggest that the magmatic activity related to the Brazilian Orogeny was, at least in the CSD, to some extent reworking of older crustal remnants.

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