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Geochemistry (Isotope Geochemistry)

An Early-Cambrian U–Pb apatite cooling age for the high-temperature regional metamorphism in the Piancó area, Borborema Province (NE Brazil): initial conclusions

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Abstract

The Borborema Province (BP) of northeastern Brazil is a complex crustal assemblage, which has undergone a polycyclic evolution during the Proterozoic. In the Piancó-Alto Brígida belt, a metamorphosed leucosome vein inserted in amphibolites has a trace element pattern suggesting a T-MORB protolith. Apatites yield a REE pattern indicating growth in equilibrium with garnet, thus pointing to its metamorphic origin. U–Pb analyses yield an age of 540 ± 5 Ma interpreted as a cooling age following amphibolite facies regional metamorphism associated with granitic emplacement at ca. 580 Ma. The resulting slow cooling rates (ranging from ca. 2.5 to $5\,^{\circ}\mathrm{C\,Ma^{-1}}$) are consistent with underplating of mafic magmas, or crustal thickening caused by nappe stacking, as possible processes governing the metamorphic evolution of the BP. ***To cite this article: B. Dhuime et al., C. R. Geoscience 335 (2003).***

Résumé

Âge de refroidissement U–Pb sur apatite du Cambrien inférieur pour le métamorphisme de haute température de la région de Piancó, province de Borborema (Nord-Est du Brésil) : premières conclusions. La Province Borborema (BP), dans le Nord-Est du Brésil, est un assemblage complexe ayant subi une évolution polycyclique durant le Protérozoïque. Dans la ceinture de Piancó-Alto Brígida, un leucosome métamorphisé, associé à des amphibolites, présente des caractéristiques d'éléments en trace, suggérant un protolithe de type T-MORB. Les apatites présentent un spectre de terres rares indiquant une croissance à l'équilibre avec le grenat, ce qui traduit une origine métamorphique. Les analyses U–Pb fournissent un âge de 540 ± 5 Ma, interprété comme un âge de refroidissement suivant le pic du métamorphisme régional daté à 580 Ma. Les taux de refroidissement faibles, compris entre 2.5 et $5\,^{\circ}\mathrm{C\,Ma^{-1}}$, sont compatibles avec des processus de sous-placage magmatique

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ou d'épaississement crustal pour expliquer l'évolution métamorphique de la BP. ***Pour citer cet article : B. Dhuime et al., C. R. Geoscience 335 (2003).***

Keywords: Borborema Province; apatite; U–Pb dating; cooling age

Mots-clés : province Borborema ; apatite ; datation U–Pb ; âge de refroidissement

Version française abrégée

1. Introduction

La province Borborema (BP), dans le Nord-Est du Brésil, est constituée par un socle paléoprotérozoïque incluant quelques noyaux archéens et des formations métasédimentaires protérozoïques. Le « domaine transversal », délimité par les deux grands cisaillements dextres de Patos et de Pernambuco, se caractérise par la présence d'assemblages volcaniques et plutoniques d'âge Mésoprotérozoïque et de bassins turbiditiques du Néoprotérozoïque terminal [2, 26]. L'existence de plutons synorogéniques (Itaporanga, Campina Grande, Acari, Caraubas, S. Rafael, Faz Nova...), datés par la méthode U–Pb sur zircons autour de 580 Ma [6,14] indique que l'ensemble des structures et le métamorphisme régional datent de cette époque. Ce travail se propose de dater, au sein du domaine de Piancó-Alto Brígida (PAB), le refroidissement associé au métamorphisme régional de haute température en utilisant le géochronomètre U–Pb sur apatite, combiné avec des analyses d'éléments en trace et de microscopie électronique à balayage. Les résultats obtenus sont comparés avec ceux connus dans d'autres parties de la BP.

2. Cadre géologique

Au sein du domaine transversal, la ceinture PAB (Fig. 1) comprend des métasédiments, des métavolcanites acides, des orthogneiss à foliation subhorizontale replissée et des gneiss anatectiques d'âge Paléoprotérozoïque présumé. Le métamorphisme régional a culminé dans le faciès amphibolite, avec anatexie à proximité des plutons granitiques. La plupart de ces plutons se sont mis en place en conditions syncinématiques à 580 Ma [6,22], qui est l'âge du pic du métamorphisme régional. La roche étudiée provient d'une bande leucocrate de 30 cm d'épaisseur, située au sein d'une séquence métabasique mésocrate à amphibole–clinopyroxène, associée à des niveaux calco-silicatés. Elle est localisée à une dizaine de kilomètres au nord du massif granitique d'Itaporanga, daté à 584 ± 2 Ma [6]. L'échantillon renferme 50% de grenat almandineux, 30% de quartz, 11% de plagioclase calcique, 6% d'amphibole verte et 1% de biotite. Les minéraux accessoires observés sont les sulfures, l'apatite, le zircon et le sphène. Le thermomètre amphibole–plagioclase [3] fournit une température d'équilibre de l'ordre de 640 °C à 4 kbar.

3. Techniques analytiques

Les apatites ont été dissoutes sur plaque chauffante en acide chlorhydrique 6 N. La séparation du plomb et de l'uranium a été effectuée selon la méthode décrite par Krogh [17]. Les blancs de procédure au cours de la période d'analyse ont varié entre 15 et 30 pg pour le Pb et moins de 5 pg pour l'U. La composition isotopique du Pb radiogénique a été déterminée en retirant le blanc, puis en supposant pour le Pb commun restant une composition déterminée d'après le modèle de Stacey et Kramers [24]. Le calcul des points expérimentaux et des âges a été effectué en utilisant le programme de Ludwig [18]. La mesure des éléments en traces a été réalisée par ICP–MS, suivant une méthode de calibration externe en vigueur à Montpellier et décrite en détails par Ionov et al. [15].

4. Résultats et discussion

L'échantillon de roche totale présente un spectre plat (Fig. 2), légèrement appauvri en terres rares légères, comparable au N-MORB. Les teneurs en terres rares sont cependant élevées (environ 50 fois les chondrites), ce qui suggère une affinité de type T-MORB [11]. L'anomalie négative en Eu suggère que le liquide initial a subi un processus de cristallisation fractionnée. L'échantillon est interprété comme un leucosome issu de la fusion partielle de basaltes altérés, similaire aux veines leucosomiques observées en domaine océanique (par exemple, [13]). Le spectre de terres rares des apatites est marqué par un appauvrissement prononcé en terres rares légères et lourdes. Ceci indique une croissance à l'équilibre avec des phases métamorphiques majeures (telles que le plagioclase et le grenat) qui incorporent ces éléments de façon privilégiée. La structure interne des apatites révèle l'absence de figures magmatiques telles que zonage ou surcroissance (Fig. 3). Ces critères permettent de définir une origine métamorphique pour les apatites analysées. Dans le diagramme Concordia (Fig. 4), les quatre fractions d'apatites définissent un âge $^{206}Pb/^{238}U$ de 540 ± 5 Ma (MSWD = 2,9). La température de fermeture de l'apatite vis-à-vis de la diffusion du Pb est de l'ordre de 450–550 °C pour des vitesses de refroidissement comprises entre 1–10 °C Ma^{-1} [8]. Dans cette partie du domaine PAB, le pic du métamorphisme régional culmine à environ 580 Ma et 640 °C. Une baisse de température depuis 640 °C à 580 Ma jusqu'à 450–550 °C à 540 Ma, permet de calculer des taux de refroidissement compris entre 2,5 à 5 °C Ma^{-1}. Ces valeurs sont similaires à celles obtenues le long du cisaillement de Patos par Corsini et al. [10] et suggèrent une évolution rétrograde et un refroidissement gouvernés par des processus de remontée isostatique et de faibles taux d'érosion. Les parties les plus métamorphiques et granitisées de la ceinture PAB ont donc subi un refroidissement lent comparable et synchrone de celui observé dans d'autres parties de la BP situées au nord du cisaillement de Patos [20]. Cette évolution est cependant différente de celle connue pour le Sud de la BP, qui a subi des taux de refroidissement comparables mais de façon plus précoce, comme l'indiquent les âges Ar de 580 Ma obtenus sur amphiboles par Neves et al. [21]. Les taux de refroidissement étant identiques sur l'ensemble de la BP (environ 3 à 5 °C Ma^{-1}), ceci suggère un diachronisme avec migration de la déformation, du magmatisme et du métamorphisme associé du Sud vers le Nord. Les faibles taux de refroidissement observés ne sont pas compatibles avec des processus de délamination et suggèrent une évolution métamorphique liée, soit à des processus de sous-placage de magmas basiques, qui réduisent l'*uplift* et réchauffent le système, soit à un épaississement crustal causé par l'empilement de nappe. Enfin, de petits bassins de molasse continentale non métamorphique sont préservés le long du cisaillement de Patos. Ces bassins sont contemporains de la mise en place de plutons granitiques de type A, d'âge Cambrien supérieur. La préservation de l'âge U–Pb sur apatite indique que cet événement n'a pas été associé à une anomalie thermique d'ampleur régionale.

5. Conclusions

L'âge de 540 ± 5 Ma, obtenu par la méthode U–Pb sur les apatites métamorphiques d'un leucosome prélevé au sein d'un complexe métabasique, est interprété comme celui du refroidissement lent de la ceinture PAB au début du Cambrien. Cet âge fait le lien avec ceux connus au Nord et au Sud et indique des taux de refroidissement lents (globalement compris entre 2,5 et 5 °C Ma^{-1}) identiques dans l'ensemble de la BP, bien que le refroidissement soit plus précoce au Sud.

1. Introduction

The Borborema Province (BP) of northeastern Brazil is a remote area of about 450 000 km^2, located between the São Francisco Craton to the south and the Amazon Craton to the northwest. It constitutes the continuation in South-America of the Pan-African mobile belts of Western Africa that occupied the northern part of Gondwana [7] (see Fig. 1). This complex domain is made up of several displaced terranes, which include large areas floored by Archean and Proterozoic crustal units and Late Neoproterozoic turbiditic basins [25]. Growing geochronological evidence suggests a polycyclic evolution during the Paleoproterozoic (2.0–2.2 Ga), Mesoproterozoic (0.95–1.10 Ga) and Neoproterozoic (0.58–0.64 Ga) periods [2,26]. The Paleoproterozoic event is probably the most important and corresponds, in the studied area, to a major period of crust formation, associated metamorphism and granite emplacement. U–Pb zircon dating of gneisses from the Transversal Domain gave ages ranging from 1.97 to 2.20 Ga [2,22]. Two major periods of felsic magmatism have been recognized, around 1.5 Ga [22] and during the 1060–930 Ma time span (the so-called Cariris Velhos event) [25]. Syn- to late-kinematic granites (Itaporanga, Campina Grande, Acari, Caraubas, S. Rafael, Faz Nova...) were intruded around 580 Ma [6,14], suggesting that all tec-

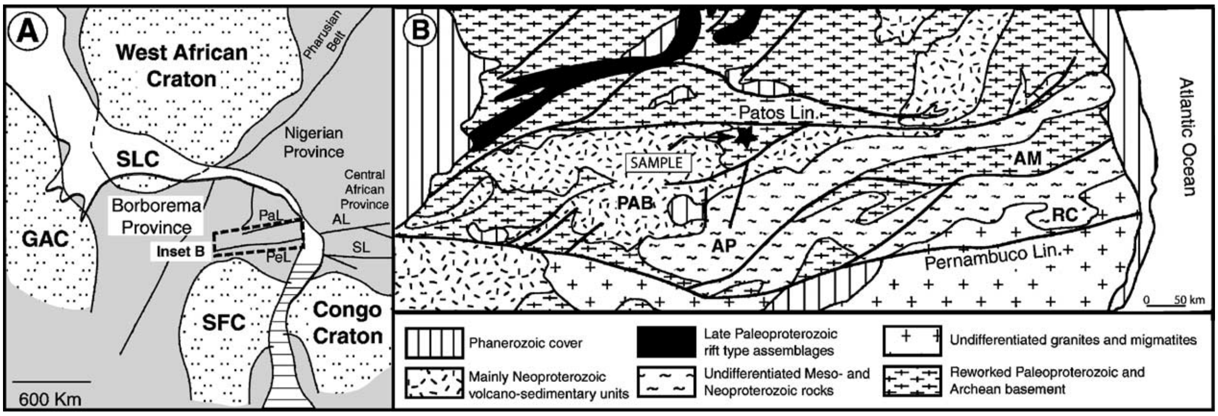

Fig. 1. **A.** Location of the Borborema Province (NE Brazil) in a pre-drift reconstruction. **B.** Geological sketch map of the Transversal zone of the Borborema Province. ★ indicates location of the studied sample. Neoproterozoic granites not represented. Abbreviations as follows: **AM**, Alto Moxoto; **AP**, Alto Pajeu; **GAC**, Guyana–Amazon Craton; **PAB**, Piancó-Alto Brígida; **RC**: Rio Capibaribe; **SFC**: São Francisco Craton; **SLC**: São Luis Craton, **PaL**: Patos Lineament, **PeL**: Pernambuco Lineament.

Fig. 1. **A.** Localisation de la province Borborema (Nord-Est du Brésil) dans une reconstruction ante-ouverture de l'Atlantique. **B.** Carte géologique simplifiée de la Zone transversale de la province Borborema. ★ indique la localisation de l'échantillon étudié. Les granites néoprotérozoiques n'ont pas été représentés. Les abréviations correspondent à : **AM**, Alto Moxoto ; **AP**, Alto Pajeu, **GAC**, craton Guyano-Amazonien ; **PAB**, Piancó-Alto Brígida ; **RC**, Rio Capibaribe ; **SFC**, craton de São Francisco ; **SLC**, craton São Luis ; **PaL**, linéament de Patos ; **PeL**, linéament de Pernambuco.

tonic features as well as the regional syn-kinematic metamorphism are of Neoproterozoic age [7]. The present study combines SEM images, ICP–MS trace element analyses and U–Pb dating on apatite in order to date cooling down to ca. 500 °C associated with the last high-temperature regional metamorphic event that affected this area. Analyses were performed on apatites from a metamorphosed mafic rock association outcropping in the Piancó-Alto Brígida (PAB) domain (Fig. 1) and the results are compared with data from other parts of the BP.

2. Geological setting

The PAB domain is located in the southern part of the BP, between two major shear zones: the Patos and Pernambuco lineaments [26]. Rocks of the PAB domain mainly consist of undifferentiated Mesoproterozoic and Late Neoproterozoic metasediments, metavolcanics and polymetamorphic gneisses, all affected by a recumbent foliation. Most granitoids (about 30% in outcrop) were intruded during the regional deformation as their thermal aureoles are syn-kinematic and coeval with the regional metamorphism [6]. Regional metamorphism grades from green-schist to amphibolite facies, low-pressure anatexis being restricted to domains of coalescent Neoproterozoic plutons such as the Itaporanga granite, the root of which includes sillimanite-bearing diatexites free of low temperature retrogression [1]. The selected sample is a 30-cm-thick garnetiferous leucocratic band interlayered within a melanocratic Fe- and Ca-rich amphibole–clinopyroxene rock from the Tito Braz gold prospect located few kilometres north of the 584 ± 2 Ma Itaporanga pluton [6]. The sample is composed of garnet (50%), quartz (30%), labradorite (11%), green amphibole (6%), biotite (1%). Fe sulphides, zircon, titanite and apatite occur as accessory minerals. Electron microprobe analyses and the amphibole-plagioclase thermometer of Blundy and Holland [3] gave an equilibration temperature of about 640 °C for an estimated pressure of 4 kbar, which we interpret as the main stage of regional amphibolite facies metamorphic overprint (data are available upon request from the first author: dhuime@dstu.univ-montp2.fr).

3. Analytical techniques

Apatites were separated by conventional mineral separation methods including high-density liquids and

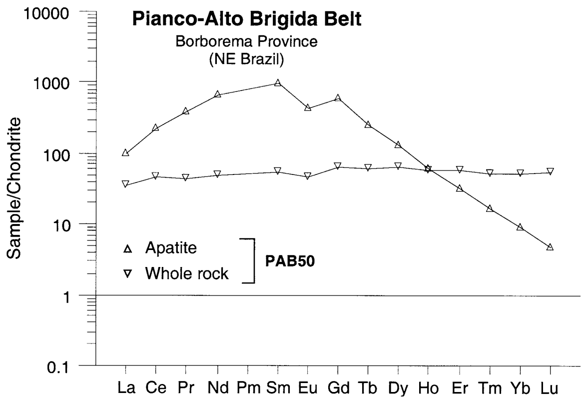

Fig. 2. Chondrite-normalized rare-earth element patterns for whole rock and apatites from the PAB 50 sample. Chondrite values are from McDonough and Sun [19].

Fig. 2. Spectre de terres rares normalisées aux chondrites pour la roche totale et la fraction d'apatite de l'échantillon PAB 50. Les valeurs des chondrites sont de McDonough et Sun [19].

a Frantz magnetic separator (e.g., [4]). Apatites were dissolved overnight in a Savillex teflon beaker on a hot plate with 6 N HCl. For isotopic analyses, lead and uranium were separated following the chemistry described by Krogh [17] and measurements were carried out on a VG Sector mass spectrometer. Total Pb blanks over the period of the analyses ranged from 15 to 30 pg and uranium blanks were less than 5 pg. The isotopic composition of radiogenic Pb was determined by subtracting the blank Pb and then the remainder, assuming a common Pb composition at the time of initial crystallisation [24]. Calculations were made using the program of Ludwig [18]. For trace element determination, after dissolution, samples were diluted in HNO_3 shortly before analyses. Concentrations were determined on a VG Plasmaquad II ICP–MS (precision of 3 to 5%) by external calibration using multi-element solutions prepared from 10 $mg\,ml^{-1}$ single elemental solutions [15].

4. Results and discussion

4.1. Trace element analyses

Trace-element analyses of the whole rock sample and of a small apatite fraction (ca. 30 mg) are reported in Table 1 and shown in the chondrite-normalized diagram of Fig. 2. The whole rock sample displays a flat to slightly LREE depleted pattern with $(La/Sm)_{CN}$ and $(La/Yb)_{CN}$ ratio close to 0.7, similar to normal MORB derived from a depleted asthenospheric mantle. The rock however is characterized by high REE content of about 50 times the chondrites, which suggests affinity with a T-MORB protolith [11]. In addition, the pattern displays a slight negative Eu anomaly despite the high modal plagioclase content, suggesting the sample has undergone some degree of differentiation and mineral segregation. The Nb/Ta ratio (13.4) is within error of the MORB value (14.4

Table 1
ICP–MS analytical data for the whole rock sample and the apatite fraction from the PAB 50 sample

Tableau 1
Résultats des analyses par ICP–MS de la roche totale et de la fraction d'apatite de l'échantillon PAB 50

Sample name	PAB 50	
Analysis	Whole rock	Apatite
Weight (mg)	50	0.032
Rb	2.0	0.31
Sr	69	196
Y	89	84
Zr	22	4.4
Nb	9.6	–
Cs	0.22	0.05
Ba	31	4.0
La	8.3	23
Ce	28	134
Pr	4.0	35
Nd	22	309
Sm	7.9	140
Eu	2.6	24
Gd	12.5	118
Tb	2.2	9.2
Dy	15.4	32
Ho	3.1	3.3
Er	8.9	5.0
Tm	1.3	0.40
Yb	8.3	1.4
Lu	1.4	0.12
Hf	0.67	–
Ta	0.71	–
Pb	3.2	1.4
Th	0.62	0.13
U	0.66	5.0
Nb/Ta	13.4	
Th/U	0.95	0.03
$(La/Sm)_{CN}$	0.68	0.11
$(La/Yb)_{CN}$	0.72	11.4
Eu/Eu^*	0.81	0.55

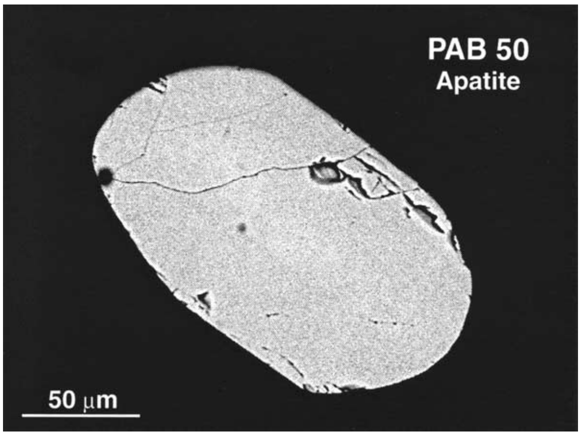

Fig. 3. SEM backscattered image of apatite from the PAB 50 sample.

Fig. 3. Image de microscopie électronique à balayage (électrons rétrodiffusés) d'une apatite de l'échantillon PAB 50.

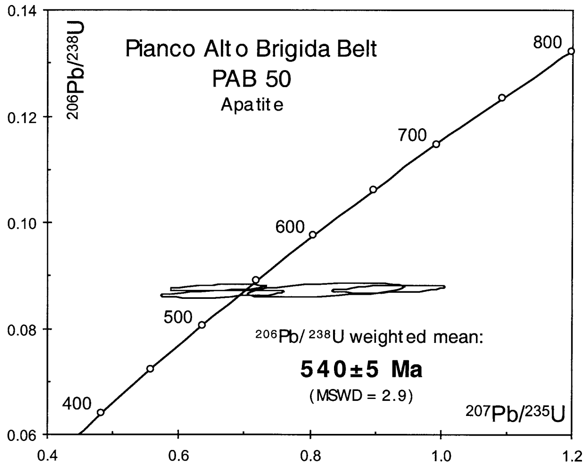

Fig. 4. U–Pb Concordia diagram for apatite fractions of the PAB 50 sample.

Fig. 4. Diagramme Concordia pour les fractions d'apatite de l'échantillon PAB 50.

±1.7 after [16]) again suggesting a depleted mantle source. The sample is then tentatively regarded as a leucosome vein resulting from hydrous partial melting of altered basalts by similarity to leucocratic melts found within the roof zones of axial magma chamber [13, e.g.]. The apatite REE-normalised pattern shows a pronounced depletion in LREE and HREE with a negative Eu anomaly. The latter is typical of apatites from various geodynamical settings and host rocks [23]. The marked depletion in both LREE and HREE indicates that growth of the apatite occurred after or during crystallisation of LREE- and HREE-rich phases, such as plagioclase and garnet respectively. These phases are major metamorphic components of the rock as they occur with a modal percentage of 11 and 50%, respectively, and can therefore seriously compete with apatite for REE during its growth.

4.2. U–Pb analyses

Apatites occur as a uniform population of small (100–150 μm) colourless translucent grains. The grains have rounded shapes and are generally free of inclusions. SEM images of polished surfaces (Fig. 3) show that they exhibit structureless internal domains. No cores, oscillatory zoning patterns or magmatic overgrowths have been observed which is consistent with a metamorphic origin. The four fractions analysed present low radiogenic Pb and U contents and consequently have low $^{206}Pb/^{204}Pb$ ratios (Table 2). Analyses are close to concordant (Fig. 4) and show a spread in the $^{207}Pb/^{235}U$ ratios but identical $^{206}Pb/^{238}U$ ratios. The four fractions provide a $^{206}Pb/^{238}U$ weighted mean age of 540 ± 5 Ma (MSWD $=$ 2.9) interpreted as our best estimate for the age of the metamorphic apatite.

4.3. Implication on the post-metamorphic evolution

Although its application is limited by relatively low U and high common Pb contents, apatite is an important accessory phase in U–Pb geochronology as it is common in many igneous and metamorphic rocks. Due to its low ionic porosity, apatite is thought to have a simple U–Pb system. This contrasts with other phosphatic phases such as monazites for example which may contain multiple growth zones within individual crystals [5] and preserve an older age in an inherited core [9]. Thus, important information on the post-peak metamorphic evolution can be obtained from the apatite results. Cherniak et al. [8] proposed a closure temperature for Pb diffusion in apatite in the range 450–550 °C for cooling rates of 1–10 °C Ma^{-1} and crystal sizes of 100–500 μm. Electron microprobe study indicates that the sample underwent a metamorphic overprint of about 640 °C, therefore exceeding the nominal closure temperature of apatite for the U–Pb system. The 540 ± 5 Ma apatite age is thus in-

Table 2
U–Pb isotopic analyses for apatite fractions from the PAB 50 sample

Tableau 2
Résultats isotopiques U–Pb des fractions d'apatite de l'échantillon PAB 50

Sample	Weigth	U	Pb*	$^{206}Pb/^{204}Pb$	$^{208}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	±	$^{207}Pb/^{235}U$	±	$^{207}Pb/^{206}Pb$	±	Apparent age (Ma)	
name	(mg)	(ppm)	(ppm)				(2σ error)		(2σ error)		(2σ error)	$^{206}Pb/^{238}U$	±
PAB 50													
Ap1	0.88	7.8	2.8	36.2	1.01	0.0873	0.0011	0.825	0.098	0.0686	0.0078	539	7
Ap2	2.43	14.4	4.9	38.0	0.94	0.0877	0.0005	0.661	0.060	0.0547	0.0047	542	3
Ap3	5.95	4.5	1.7	35.2	1.05	0.0875	0.0006	0.920	0.070	0.0763	0.0054	541	4
Ap4	7.04	11.5	4.8	33.6	1.08	0.0866	0.0006	0.667	0.077	0.0567	0.0061	535	4

terpreted as recording a cooling point on the downside of regional metamorphism and it is suggested that the temperature has dropped from 640 °C at ca. 580 Ma (the age of peak metamorphism) to 450–550 °C at 540 Ma. This indicates that after peak metamorphism, the temperature decreased slowly at a rate of 2.5 to 5 °C Ma^{-1}. Similar values (ranging from 3 to 4 °C Ma^{-1}) were calculated from Ar datings along the Patos shear zone and in the Seridó area [10]. Such slow cooling rates suggest that denudation occurred by processes consistent with isostatic recovery and low erosion rates. This contrasts with tectonically assisted retrograde evolution associated, for example, with late metamorphic thrusting and nappe stacking and with the differential uplift and exhumation of deep crustal units along major shear zones. It is also noteworthy that the 540 Ma apatite age is identical to the 540–550 Ma Ar amphibole ages provided by rocks from the western termination of the Patos lineament and from the Cedro belt, north of this lineament [20]. Since the amphibole closure temperature for Ar is similar to the U–Pb closure temperature of apatite, it is concluded that crustal units on each side of the lineament undergone the same post-metamorphic cooling history. Conversely, rocks from the southern part of the BP (Caruaru area) yielded identical cooling rates (ca. 5 °C Ma^{-1}), but cooling down to 500 °C occurred earlier, at ca. 580 Ma [21]. This suggests a possible diachronous evolution for the tectonometamorphic event in the BP during the Braziliano/PanAfrican time. This period of tectonism, metamorphism and igneous emplacement represents a major period of plate tectonic activity resulting in the final assembly of the Gondwana supercontinent. The low cooling rates observed in the whole BP, except in the vicinity of major shear zones where cooling had reached values of 20 °C Ma^{-1} (e.g., [20]), and the possible diachronism are not compatible with delamination phenomena which are typically associated with uplift and high erosion rates. Underplating of mafic magmas, which reduces uplift while adding heat to the system, or crustal thickening caused by nappe stacking and responsible for partial melting and granite emplacement, are more likely processes to explain the Neoproterozoic metamorphic evolution of the BP and the associated long-lived thermal anomaly. Lastly, relics of non-metamorphic continental molassic basins are preserved along the Patos lineament [7]. Molasse deposition was coeval with felsic volcanism and with emplacement of A-type hypo-volcanic granites of Late-Cambrian age in the northern part of the BP [12]. Preservation of the 540-Ma apatite age indicates that this magmatic activity was not associated with a significant thermal anomaly of regional extent.

5. Conclusions

Conventional U–Pb analyses of apatite extracted from a leucosome vein of T-MORB affinity outcropping in the Piancó-Alto Brigida (PAB) domain of the Borborema Province (BP) provide an age of 540 ± 5 Ma. This value is interpreted as a cooling age following regional amphibolite facies metamorphism with cooling rates of about 2.5 to 5 °C Ma^{-1}. These are similar to cooling rates obtained from other parts of the BP although cooling occurred earlier in the south suggesting a possible north–south diachronic evolution.

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