Age of pegmatites from eastern Brazil and implications of mica intergrowths on cooling rates and age calculations

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Abstract

U–Pb and K–Ar dating of selected minerals from different types of pegmatites in the northern region of the eastern Brazilian pegmatite province (EBPP) are reported. A concordant U–Pb age of 498 ± 3 Ma for monazite from a simple, quartz-feldspar pegmatite without gem minerals corresponds to the crystallization age related to the Brasiliano-Pan-African posttectonic magmatic stage. This correlation is substantiated by a discordant $^{207}\text{Pb}/^{206}\text{Pb}$ age of 498 ± 11 Ma for a zircon fraction that comprises large, prismatic crystals of pegmatitic origin with recent lead loss. The U–Pb isotope systematics of another zircon fraction composed of fine-grained, transparent grains indicates inheritance from older basement rocks.

K–Ar age determinations for the core and rims of very large crystals of muscovite from more evolved, beryl-bearing pegmatites yield a mean age of 498 ± 4 Ma. However, K–Ar dating of biotite enclosed in muscovite crystals results in a younger age of 485 ± 4 Ma. This difference in age of ca. 13 Ma is interpreted to correspond to the time span for cooling from 400 to 350 °C (reported closure temperatures for K–Ar isotope systems of coarse-grained muscovite and biotite, respectively), which suggests a mean cooling rate of 3.3 °C/Ma. As such, it took 60 Ma for the pegmatite and its country rocks to cool from 600 °C (approximate crystallization temperature of pegmatite) to the closure temperature of 400 °C of muscovite, thus leading to an emplacement age of 560 Ma for the fertile pegmatite. This date is within the range of ages obtained for nearby fertile granites. The beryl-bearing pegmatites may be late tectonic and related to the main stage of granulogenesis of the Brasiliano orogeny, not posttectonic as determined for the northern, unfertile pegmatite.

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1. Introduction

Brazil is one of the largest producers of colored gemstones such as aquamarine, emerald, kunzite, alexandrite, tourmaline, and topaz (Morteani et al., 2000; César-Mendes et al., 2001; Pinto and Pedrosa-Soares, 2001). Large quantities and varieties of gemstones are produced in the northeastern and eastern pegmatite provinces. Of these, the eastern Brazilian pegmatite province (EBPP), sometimes also called the Oriental pegmatite province, is the largest in area (approximately 800 km long and 150 km wide) and of the greatest

importance. The pegmatites are spread over eastern Minas Gerais, western Espírito Santo, northern Rio de Janeiro, and southern Bahia (Fig. 1). The EBPP is characterized not only by its geographic location, but also its particular geotectonic setting in a Neoproterozoic-Cambrian orogenic belt generated during the Brasiliano-Pan-African cycle, which consisted of a set of orogenies that lasted from 850 to 550 Ma (Pinto and Pedrosa-Soares, 2001). The majority of the pegmatites of the EBPP are related to granite intrusions into the Brasiliano mobile belts generated during the consolidation of the Gondwana supercontinent. They are considered residual melts derived from S-type (product of the total or partial melting of a sedimentary source) and I-type (derived from igneous sources) granites (Lobato and Pedrosa-Soares, 1993; Pedrosa-Soares et al., 1999; Pinto and Pedrosa-Soares, 2001). Pegmatite melts derived directly

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Fig. 1. Outline of the eastern Brazilian pegmatite province (EBPP) with location of the dated pegmatites in Areas 1 and 2. (Area 1) Simplified geological map of the region of the Rio do Prado pegmatite. (Area 2) Simplified geological map of the region of the Ipê and Golconda pegmatites (geology modified after Oliveira et al., 1997; Pedrosa-Soares and Wiedmann-Leonardos, 2000).

Table 1
Age compilation of the literature about the eastern Brazilian pegmatite province

Region and (district)	Age (Ma)		References
Caparaó/Manhuaçu (Ca)	556 ± 16; 505 ± 10	(m)*	Dirac and Ebert, 1967
Caparaó/Manhuaçu (Ca)	469 ± 15	(m)*	Cordani et al., 1973
Eugenópolis /Caparaó (Ca)	454 ± 23	(m)*	Delhal et al., 1969
Eugenópolis /Manhuaçu (Ca)	476 ± 15	(f)**	Cordani et al., 1973
Eugenópolis/Caparaó (Ca)	452 ± 15; 454 ± 15	(m, f)**	Lendent and Pastels, 1968
Bicas (JF)	511 ± 14; 483 ± 12	(m)*	Dirac and Ebert, 1967
Juiz de Fora (JF)	480 ± 8	(b)*	Cordani et al., 1973
Juiz de Fora (JF)	1096 ± 65; 1047 ± 63	(m)*	Bigazzi et al., 1971
Serra dos Órgãos (JF)	408 ± 11	(m)*	Cordani and Teixeira, 1979
Serra dos Órgãos (JF)	471 ± 14	(m)*	Bigazzi et al., 1971
Serra dos Órgãos (JF)	512 ± 19	(f)**	Cordani and Teixeira, 1979
Serra dos Órgãos (JF)	464 ± 25	(b)*	Cordani et al., 1973
Araçuaí (Ar)	467 ± 18; 490 ± 12	(m)*	Sá, 1977
Serra Azul (SMIt)	502 ± 31	(m)*	Marciano et al., 1993
Sabinópolis (SMIt)	529 ± 13	(m)*	Marciano et al., 1993
Sta. Maria Itabira (SMIt)	519 ± 10	(m)*	Marciano et al., 1993
Sta. Maria Itabira (SMIt)	531 ± 22	(mz) ^c	Bilal et al., 1995
Rio Piracicaba (SMIt)	525 ± 11	(m)*	Marciano et al., 1993
Rio Piracicaba (SMIt)	545	(f)**	Herz, 1970
Vitória da Conquista (VC)	660 ± 37; 709 ± 20	(m)*	Mascarenhas and Garcia, 1989
Governador Valadares (GV)	497 ± 13; 501 ± 14	(m, f)**	Marciano et al., 1993

*K–Ar; **Rb–Sr; ***U–Pb.; (m) muscovite; (f) feldspar; (mz) monazite; (b) biotite. Districts: Ca = Caparaó; JF = Juiz de Fora; Ar = Araçuaí; SMIt = Santa Maria de Itabira; VC = Vitória da Conquista; GV = Governador Valadares.

from the host rocks through anatexis (partial melting) are also possible (Lobato and Pedrosa-Soares, 1993).

Geochronological data for the pegmatites from the EBPP show a great dispersion of ages ranging from 1100 to 408 Ma (Table 1). Older pegmatites, such as those in the Bahia region, were probably generated during the Transamazonian orogeny (~2000 Ma) and submitted to partial isotopic reequilibration during the Brasiliano-Pan-African tectonothermal event (Cordani and Sato, 1985). Because the Juiz de Fora pegmatite is even older, it is reasonable to propose that the same event occurred in this region. Younger pegmatites (600–400 Ma) are believed to have been generated during the Brasiliano-Pan-African orogeny, during which two main episodes of granitogenesis can be distinguished in the EBPP (Söllner et al., 1987; Sial et al., 1999; Bilal et al., 2000; Pinto and Pedrosa-Soares, 2001): a pre- to syntectonic (600 Ma; Sial et al., 1999) and a tardi to posttectonic (560–480 Ma; Sial et al., 1999). Between these two granitogenesis stages, there was a magmatic quiet period that lasted for approximately 40 Ma.

Rb–Sr and K–Ar (Ar–Ar) dating methods are often used to date pegmatites. In many cases, U–Pb is difficult to apply because of the scarcity of U-bearing minerals (e.g. zircon, monazite, titanite, xenotime, columbite–tantalite). In addition, pegmatite zircons are frequently metamict, normally with high U contents. This characteristic results in very discordant U–Pb data and inaccurate ages. Furthermore, pegmatites can contain many inherited zircons, and therefore, extra care is needed to select the proper zircon type for dating.

Most published geochronological data for the pegmatites from the EBPP are based on K–Ar and Rb–Sr mineral dating (Table 1). In an attempt to verify the hypothesized magmatic stages, we present the results of U–Pb dating on monazite and zircon and K–Ar dating on micas (muscovite and biotite) from selected pegmatites from the Governador Valadares and Rio do Prado regions, located in the northern portion of the EBPP (Fig. 1). We also compare the crystallization ages of monazite- and zircon-bearing simple pegmatites with beryl-bearing, fertile pegmatites with no U-bearing minerals from the same region.

2. Geological framework

The region of northeastern Minas Gerais and southern Bahia is made up of two different geotectonic units: the São Francisco Craton and the Araçuaí mobile belt (Fig. 2). The São Francisco Craton is an Archean block in eastern Brazil that reached crustal stability at approximately 1700–1800 Ma. The Araçuaí mobile belt is a monoclinic Neoproterozoic foldbelt partially surrounding the São Francisco Craton that roughly marks the southern limit with the Atlantic belt at the 21°S parallel (Fig. 2). The major features of these belts were produced during the Brasiliano-Pan-African orogeny due to the collision between the São Francisco and West Congo Cratons (Sial et al., 1999). According to Siga (1986), the granite bodies intruding the Araçuaí mobile belt are pre-tectonic (>650 Ma), syn- to late

Fig. 2. Geological outline of the São Francisco and Congo Cratons and marginal belts (modified after Pedrosa-Soares et al., 1999).

tectonic (650–550 Ma), and posttectonic (500–450 Ma) in relation to the Brasiliano orogeny.

Fig. 1 shows the simplified geology of the northeastern area of Minas Gerais. Special attention is directed to the Jequitinhonha (Jequitinhonha Complex in Area 1) and Governador Valadares (São Tomé Formation in Area 2) areas, which are the sources of the investigated pegmatites.

The Jequitinhonha Complex comprises a thick pile of kinzigites, gneisses, and migmatites with alternating leucocratic and melanocratic bands, quartzite, and calc-silicate rocks (Almeida and Litwinski, 1984). The model ages of paragneisses of the Jequitinhonha Complex, as determined by Sm–Nd, range from 1730 to 1610 Ma (Celino et al., 2000).

Table 2
U–Pb age data for monazites and zircons from the Rio do Prado pegmatite, Minas Gerais, Brazil

Samples ^a	Sample (wt/mg)	U (ppm)	Pb (ppm)	²⁰⁶ Pb/ ²⁰⁴ Pb (measured)	²⁰⁸ Pb/ ²⁰⁶ Pb (radiogenic)	Isotopic ratios ^b				Rho ^c				Apparent ages (Ma ± 2 sigma)	
						²⁰⁶ Pb/ ²³⁸ U	2SE%	²³⁸ U/ ²⁰⁶ Pb	2SE%	²⁰⁷ Pb/ ²³⁵ U	2SE%	²⁰⁷ Pb/ ²⁰⁶ Pb	2SE%	²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²⁰⁶ Pb

^a Samples: A. Monazites: 0.25–0.8 mm, transparent yellow, abraded 1 h B. Pegmatite zircons: long prismatic, translucent, 0.5–1.0 mm, abraded 6 h C. Zircons: transparent, small oval grains, abraded 31 h
^b Isotopic ratios corrected for fractionation, blank (30 pg), and age-related common lead (Stacey and Kramers, 1975).
^c Correlation between ²⁰⁷Pb/²³⁵U and ²⁰⁶Pb/²³⁸U errors.

The Rio Doce valley in the Governador Valadares region comprises rocks such as gneisses, a supracrustal schist sequence, sericite quartzite, and intrusive granitoids (Almeida, 1981; Cunningham et al., 1996; Oliveira et al., 1997; Nalini et al., 2000a; Pedrosa-Soares and Wiedmann–Leonardos, 2000). The whole-rock age of the gneisses, determined by Rb–Sr, is 560 ± 15 Ma (Da Silva et al., 1987), whereas K–Ar ages range from 525 to 670 Ma. Nalini et al. (2000a) date zircon fractions from the Galiléia and Urucum intrusive granitic complexes, both near Governador Valadares, by U–Pb. The ages, based on concordia upper intercepts, are 594 ± 6 and 582 ± 2 Ma, respectively, though the monazite fraction from the Urucum Complex yields a concordant age of $576\text{--}573 \pm 4$ Ma. In the Urucum Complex, inherited zircons dated at 2.2 Ga can also be found.

The metamorphism of the Rio Doce rocks is greenschist to amphibolite facies, but locally sedimentary turbiditic features can still be recognized in the banded schist (Pedreira et al., 1997).

The São Tomé Formation is the most significant economic unit of the Rio Doce group because it hosts many gem-producing pegmatites. Biotite gneiss is the main rock type of this formation, but quartzite, tourmalinite, amphibolite, graphitic schist, and calc-silicate rocks are also observed. Its contact with other units is by thrust faults generated by a compressive event during the Brasiliano orogeny. The unit hosts granites, tonalites, granodiorites, and pegmatitic bodies (Drumond et al., 1997). Its age is unknown, but it must be older than the 650 Ma intrusive complex that cuts it (Brandalise, 1991; Cunningham et al., 1996). The metamorphism of the São Tomé metasediments is of middle to high amphibolite facies with retrograde metamorphism to lower amphibolite facies, with pressures of 4.5–5 kbar and temperatures of 530–650 °C (Tallarico and Pereira, 1997).

3. Location and sample description

Monazite and zircon samples for U–Pb dating were collected from a 5 m wide, texturally homogeneous pegmatite named Rio do Prado (Viana, 1997), which is of simple mineralogy (quartz, feldspars, altered mica, and black tourmaline) and located in the Rio do Prado region, lower Jequitinhonha Valley, extreme northeast Minas Gerais (Fig. 1). Yellow, transparent monazite crystals are exceptionally large (0.2–0.8 mm), typical of coarse-grained pegmatites. Two fractions of morphologically different zircons were selected for dating (Table 2). The first fraction is composed of translucent to turbid, 0.5–1.0 mm prismatic grains. Their large size indicates that these crystals belong to pegmatite mineralogy. The second fraction is composed of fine-grained (<0.15 mm), totally transparent, oval zircon grains. Their morphology and size suggest that these zircons are inherited.

Four mica samples from the Ipê and one from the Golconda pegmatites were selected for K–Ar geochronology. The two pegmatites are located near Governador Valadares City (Fig. 1) and composed of quartz, feldspar, beryl, mica (muscovite and biotite), tourmaline (black, green, or bicolor), and columbite-tantalite. These more than 100 m long, 20 m wide pegmatite bodies show textural and well-defined compositional zonation.

Four Ipê mica samples (RbI-1, RbI-2, RbI-3, and RbI-5) were collected in the marginal zone, whereas RbI-4 was collected in the wall zone. Sample RbG-1 from the Golconda pegmatite comes from the wall zone. Most crystals form large mica books of up to 20 cm wide. Some show pseudohexagonal shape, whereas others present a fish-tail shape. They have a light-brown color and no apparent alteration. Samples RbI-1 and RbI-5 are made of an intergrowth of two micas, in which the center is composed of biotite and the border of muscovite. All other samples are muscovite, including the mica from the Golconda pegmatite. One large muscovite crystal (RbI-2, 15 cm wide) was dated at five different points (x, y, z, v, and w).

4. Analytical methods

The U–Pb dating of zircons and monazites was performed in the isotope laboratory of the Geological Survey of Finland. The decomposition of zircon and monazite and the extraction of U and Pb for conventional isotopic age determinations mostly followed the procedure described by Krogh (1973). ^{235}U – ^{208}Pb (zircon) and ^{235}U – ^{206}Pb (monazite) spiked and nonspiked isotopic ratios were measured using a VG Sector 54 thermal ionization multicollector mass spectrometer. The measured lead and uranium isotopic ratios were normalized to the accepted ratios of SRM981 and U500 standards. The U–Pb age calculations used the PbDat-program (Ludwig, 1991), and the discordia lines were fit using the Isoplot/Ex program (Ludwig, 1998).

Analyses using the K–Ar method were performed at the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in Hannover, Germany. Argon was determined by total fusion, static isotope dilution analyses on a MAT CH 4 mass spectrometer. Concentration of K was determined using Li as an internal standard by flame photometry. The mean standard deviations (2 sigma) of K and radiogenic Ar are approximately .75 and .3%, respectively. The argon isotope ratios were corrected for mass discrimination and system blank and calibrated against an interlaboratory standard (biotite SN). Compared with the median information of interlaboratory compilation (Odin, 1982), the data for a standard glauconite is approximately GI-HE 1% younger. The constants used for the age calculation followed the norms recommended by IUGS (Steiger and Jäger, 1977).

5. Results and discussion

5.1. U–Pb dating

The monazite grains selected were first air-abraded for an hour to remove the grain surfaces, which may have suffered postcrystallization lead loss. The measured $^{206}\text{Pb}/^{204}\text{Pb}$ ratio of approximately 25,200 indicates a virtual absence of common lead and a high uranium concentration, typical of pegmatitic monazites (Table 2). When the decay constant errors are included, the monazite fraction gives a concordant age of 498 ± 3 Ma (Fig. 3), which reflects the time of pegmatite crystallization.

Two fractions (B and C) of morphologically dissimilar zircons were analyzed by U–Pb (Table 2). The large crystals (B; Table 2) were air-abraded for 6 h, whereas the fine-grained zircons (C; Table 2) were air-abraded for 31 h. Both fractions yielded discordant ages. However, the U–Pb data (Table 2) clearly show distinct $^{206}\text{Pb}/^{204}\text{Pb}$ and radiogenic $^{208}\text{Pb}/^{206}\text{Pb}$ ratios, which distinguish $^{207}\text{Pb}/^{206}\text{Pb}$ ages and U concentrations for the zircon fractions B and C. These differences suggest distinct origins for the two zircon fractions. Low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios and high uranium concentrations are quite common in pegmatite zircons. The large, pegmatite zircons of fraction B give a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 498 ± 11 Ma (Table 2), similar to the concordant monazite age. Therefore, it may be possible to plot the U–Pb data from these zircons together with the monazite age data. The resulting discordia line goes through the 0 Ma point (Fig. 3), evidence of modern lead loss from the high uranium pegmatite zircons. In contrast, the U–Pb data from fraction C indicate an older, inherited origin for the zircons (Fig. 3). If the radiogenic lead loss in these small zircons is caused by the ca. 500 Ma tectonothermal Brasiliano event, their age can be approximated as 2.0 Ga, consistent with the Paleoproterozoic Transamazonian orogeny. However, further U–Pb data are needed to specify the age of these fine-grained, inherited zircons.

5.2. K–Ar Age determination

Muscovite samples from the walls of the Ipê (RbI-4) and Golconda (RbG-1) pegmatites yielded ages of 496 ± 4 and 494 ± 4 Ma, respectively. The results listed in Table 3 show that, for the Ipê pegmatite, the ages obtained from the marginal (RbI-1, RbI-5) and wall zones are very similar.

In the marginal zone of the Ipê pegmatite, intergrowths of biotite and muscovite are common. Two samples composed of biotite enclosed within muscovite (RbI-1 and RbI-5) were analyzed. The muscovite yields an average age of 498 ± 4 Ma, whereas the biotite samples, though enclosed in muscovite and therefore older, show a younger age of 485 ± 4 Ma. This age difference of 13 Ma can be explained by the different closure temperatures for K–Ar isotope systems in mica during cooling. Closure temperature ranges of 350 ± 50 °C for muscovite and 300 ± 50 °C

Fig. 3. Tera-Wassenaar concordia plot of U–Pb age data for monazites and zircons from the Rio do Prado pegmatite (Minas Gerais, Brazil).

for biotite have been reported by many authors (Hanson and Gast, 1967; Jäger et al., 1967; Purdy and Jäger, 1976; Harrison et al., 1985; Lister and Baldwin, 1996). The closure temperature depends on factors such as grain size and grain shape, though further refinement of experimental data is needed (Möller et al., 2000). In the case of the studied pegmatites, the mica flakes are larger and thicker than 1 cm. Larger grain sizes imply higher closure temperatures (Lister and Baldwin, 1996). Using the higher closure temperatures of 400 °C for muscovite and 350 °C for biotite, the age difference of 13 Ma of biotite and muscovite corresponds to the time span for cooling from 400 to 350 °C. The cooling rate for the pegmatite can therefore be estimated as 3.3 °C/Ma.

Five datings were performed at different points in the 15 cm muscovite sample RbI-2 (Table 3) from the Ipê pegmatite to verify the influence of grain size on closure ages. Analyses were performed on two samples extracted from the central portion (u and v) and three near the border (x, y, and z) of the crystal. Within error limits, no age differences could be detected from center to border, which indicates that the closure temperature in the central and marginal parts of the crystal was reached at approximately the same time.

Some considerations are necessary to analyze the cooling ages of 498 ± 4 Ma for muscovite and 485 ± 4 Ma for biotite. The pegmatites intruded medium- to high-grade fibrolite–garnet–plagioclase–muscovite–biotite–quartz schists of the São Tomé Formation. A high metamorphic

grade is also found regionally (Tallarico and Pereira, 1997). If the calculated cooling rate of 3.3 °C/Ma (which is consistent with the 2–5 °C/Ma cooling rate determined by Möller et al. (2000) for terrains in Tanzania that also were generated during the Pan-African orogeny) remained unchanged since the crystallization of the pegmatite during peak metamorphic conditions, it is possible to calculate the real crystallization age of the micas. Pegmatite melts usually crystallize at approximately 600 °C, which should be the approximate peak metamorphic temperature of the country rock, as deduced from the mineral parageneses. Therefore, 60 Ma passed since the pegmatite and its country rocks

Table 3

Muscovite and biotite ages by K–Ar method from pegmatites of the Governador Valadares region (GV)

Sample	K (wt%)	Rad. (nl/g)	Ar (%)	Age (Ma)	Mineral/zone
RbI-2z	8.48	188.4	97.3	496.8 ± 4.1	Muscovite/marginal
RbI-2v	8.45	189.5	97.7	499.9 ± 4.1	Muscovite/marginal
RbI-2w	8.52	188.6	97.4	495.0 ± 4.1	Muscovite/marginal
RbI-2y	8.47	189.2	97.4	498.8 ± 4.1	Muscovite/marginal
RbI-2x	8.46	189.5	97.3	499.9 ± 4.8	Muscovite/marginal
RbI-2	8.46	188.5	97.2	498.2 ± 4.1	Muscovite/marginal
RbI-1	7.73	167.5	97.7	485.3 ± 4.2	Biotite/marginal
RbI-1	8.58	192.1	97.2	499.8 ± 4.1	Muscovite/marginal
RbI-5	8.52	190.7	98.1	499.9 ± 4.1	Muscovite/marginal
RbI-5	7.82	169.5	98.2	485.5 ± 4.2	Biotite/marginal
RbI-4	8.41	186.0	98.0	496.2 ± 4.1	Muscovite/wall
RbG-1	8.64	190.7	97.7	493.8 ± 4.1	Muscovite/wall

Notes: z, v, w, y and x are different points of the RbI-2 sample.

cooled from 600 to 400 °C, the closure temperature for muscovite. Thus, the crystallization age estimated for the micas would be approximately 560 Ma, which is higher than the 500 Ma age determined for monazite and zircon from the simple pegmatite. Age determinations by Nalini et al. (2000a) for syntectonic S-type granites of the Urucum suite, located near Governador Valadares, give U–Pb zircon ages of 582 ± 2 and U–Pb monazite ages of $576\text{--}573 \pm 4$ Ma. On the basis of geochemical studies, Nalini et al. (2000b) find that the Urucum batholith could represent the parental magma for nearby pegmatites; consequently, the age of these pegmatites will not deviate substantially from the age of the progenitor Urucum granite. We conclude that the calculated crystallization age of 560 Ma for the studied fertile pegmatites, based on the regional cooling rate of 3.3 °C/Ma, is plausible in light of the geochronological and geochemical information available for the area. Considering the two major magmatic stages of the Brasiliano tectonothermal event, as distinguished by Söllner et al. (1987), Sial et al. (1999), Bilal et al. (2000) and Pinto and Pedrosa-Soares (2001), the 560 Ma age of the beryl-bearing, more evolved pegmatites from the Governador Valadares region is related to the late-tectonic magmatic stage. The 500 Ma age obtained for the simple, unfertile pegmatite of the Rio do Prado region, in contrast, is related to the posttectonic stage.

6. Conclusions

The results of our investigations show that two pegmatite generations can be distinguished in the northern portion of the EBPP. The older, 560 Ma pegmatites are related to the main stage of granitogenesis of the Brasiliano-Pan-African orogeny. They are more complex and evolved than the second pegmatite generation, which is dated at 500 Ma and related to the late stage of granitogenesis. These results not only strengthen current knowledge about the two main episodes of granitogenesis in the EBPP, but also extend the two stages to pegmatite generation. Furthermore, the different ages determined for biotite and its host, muscovite, provide an estimation of the cooling rate—3.3 °C/Ma—of the crust during the final stages of the Brasiliano orogeny.

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