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Neoproterozoic anorogenic magmatism in the Southern Bahia Alkaline Province of NE Brazil: U–Pb and Pb–Pb ages of the blue sodalite syenites

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Abstract

Blue sodalite syenite is a rare rock, and the Southern Bahia Alkaline Province (SBAP) is the only place in Brazil where economic deposits are found. This province forms part of the Archaean to Paleoproterozoic São Francisco craton, and contains a few batholiths, a large number of stocks and hundreds of dykes. Its southern part lies close to the tectonic contact between the craton and the Neoproterozoic Araçuaí mobile melt. Blue sodalite-bearing syenites are found in almost all the igneous bodies of the SBAP as dykes or pegmatitic masses hosted by nepheline syenite. Economically viable quantities for the production of dimension stones are found only in the Floresta Azul alkaline complex, the Itaju do Colônia and Rio Pardo stocks and the Itarantim batholith. U–Pb ages obtained for titanite from Itaju do Colônia (732 ± 8 Ma) and Rio Pardo (714 ± 8) and Pb–Pb evaporation ages of zircon from Floresta Azul (696 ± 3 Ma) and Itarantim (722 ± 5 Ma). The geochronology of the SBAP shows that the anorogenic alkaline magmatism persisted for at least 58 Ma, demonstrating an extensional tectonic environment in the southern part of the São Francisco craton at this time. The data show that the rift phase which preceded the formation of the Araçuaí orogen was active until at least 700 Ma. The reported ages are similar to those found for the nepheline syenite host bodies, which supports the conclusions of the previous petrologic study demonstrating that blue sodalite is formed during the crystallization of these bodies. Two different processes are involved. In the magmatic process, sodalite occurs as disseminated and interstitial crystals among alkali feldspar

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crystals, and is associated with calcite and cancrinite formed by destabilization of nepheline. In the metasomatic process, discontinuous bands of sodalite are in sharp contact with nepheline syenite pegmatite, and its crystal aggregates often contain relict textures of nepheline and albite been replaced by sodalite.

Keywords: Blue sodalite; Syenite; Neoproterozoic; Anorogenic magmatism; Brazil

1. Introduction

Blue sodalite syenite are extremely rare, with only three known large deposits (Bancroft and Ice River in Canada, and Litchfield in the USA; Fraser, 2001), although less voluminous occurrences of blue sodalite syenites are associated with nepheline syenite and carbonatite complexes such as Mont Saint Hilaire complex, Canada (Currie et al., 1986), Badakhshan Province, Afganistan (Cook, 2004), Cerro Sapo, Bolivia (Schultz et al., 2004) and Swartbooisdrif, Namibia (Drüpprel et al., 2005). In Brazil deposits of blue sodalite syenites are restricted to the Southern Bahia Alkaline Province (SBAP; Fig. 1), which is the only known case of Neoproterozoic silica-undersaturated alkaline magmatism in the São Francisco craton.

Silica-undersaturated alkaline magmas are normally formed within continental plates where they are common in rift systems, within oceanic plates associated with hot spots, or as products of mantle plumes. The genesis of these magmas is usually attributed to small degrees of mantle melting. Due to their association with anorogenic environments, these rocks are important geodynamic markers which are useful in reconstructing the geodynamic evolution of old terrains.

The alkaline rocks of southern Bahia have been known since the 1960s (Fujimori, 1967), but very little is known about the genesis of the sodalite syenites

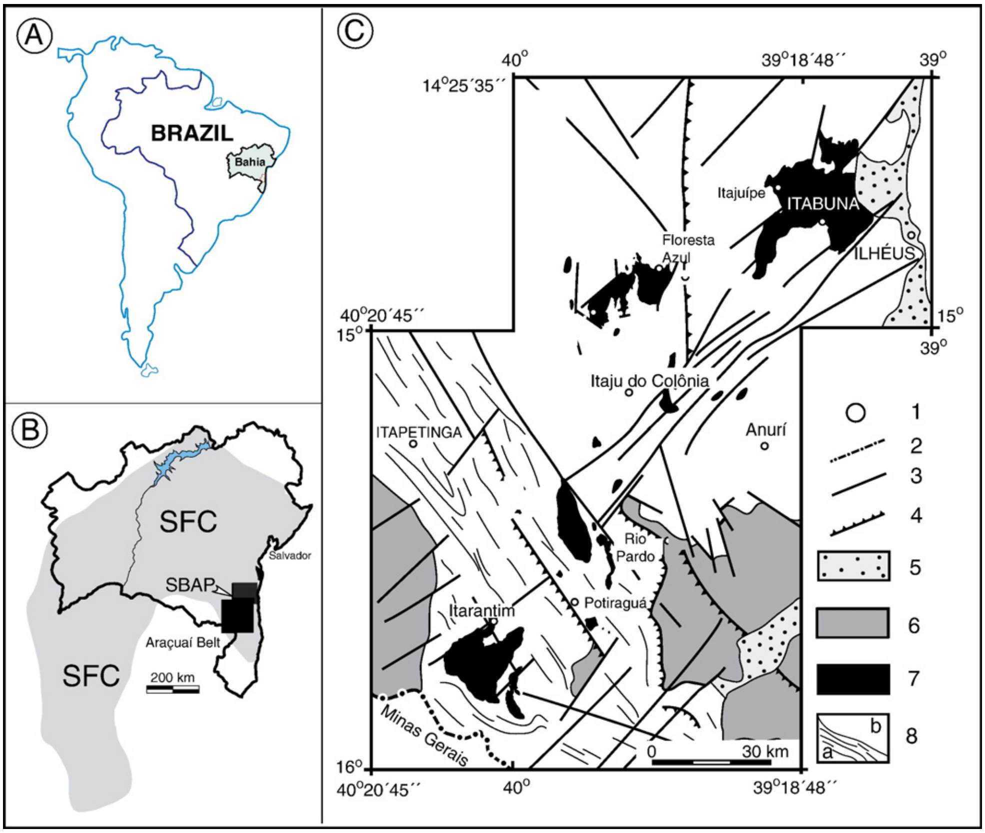

Fig. 1. Location of the State of Bahia in South America [A]. Geological sketch of Bahia with limits of the São Francisco craton (SFC) [B]. Location of the Southern Bahia Alkaline Province (SBAP) [C]: city [1], state divide [2], fracture or fault [3], thrust fault [4], recent sediments [5], Rio Pardo basin [6], alkaline rocks of the SBAP [7], gneiss–migmatite [8a] and granulite [8b] terrains.

(Conceição and Otero, 1996). This is a reflection of the sporadic nature of the previous studies, which were mainly directed towards regional geology and reconnaissance geochronology (Cordani, 1972; Souto, 1972; Teixeira et al., 1997), in which the blue syenites are mentioned only in passing. Previous geochronological investigation at SBAP, using K–Ar, Ar–Ar and Rb–Sr methods (e.g. Mascarenhas and Garcia, 1987), showed wide variation between 760 and 490 Ma, and a definition of the ages of intrusion and the mineralization was impossible.

During the last five years our group has undertaken a number of studies (Cunha, 2003; Oliveira, 2003; Menezes, 2005; Rosa et al., 2005a,b) which mapped the bodies and studied their petrography and geochemistry in order to understand their genesis. Due to the size of the province (8000 km^2), these studies are still in progress. Here we present the U–Pb and Pb–Pb geochronological data obtained for four of the economic deposits of blue sodalite syenite, and discuss the significance of these rocks for the geodynamics of the Brasiliano (Pan-African) orogeny in this part of the São Francisco craton. We also present some aspects of their genesis.

2. Regional context

The study area is part of the Archaean–Paleoproterozoic São Francisco craton, and the southern part of the province is close to the tectonic contact between the craton and the Neoproterozoic Araçuaí mobile belt (Fig. 1B). In addition to the old basement, Mesoproterozoic basic magmatic rocks, Neoproterozoic sediments and alkaline magmatic rocks are present (Fig. 1C).

Two different metamorphic units form the basement to the SBAP. The better-known unit occurs in the northern part and is composed of high-grade rocks usually referred to as the Itabuna belt. The granulites include orthogneiss with tholeiitc, calc-alkaline and shoshonitic affinities. The last granulitic metamorphism to affect these terrains occurred between 2.2 and 2.0 Ga. Structural and geophysical data demonstrate that westwards thrust faults are present, and these are believed to have formed during a Paleoproterozoic collision (Barbosa and Sabaté, 2004). The other basement unit occurs in the south, and has a faulted contact with the granulites (Fig. 1B). It consists of amphibolite-grade gneiss-migmatites.

The Mesoproterozoic rocks are basic dykes (D'Agrella Filho et al., 1990) intruded between 1078 and 1012 Ma. During the Neoproterozoic a number of alkaline, mainly nepheline syenite bodies were intruded. Continental sedimentary basins also developed, of which the best-known is the Rio Pardo basin (Pedreira, 1999) whose basal conglomerates have syenite pebbles, some of which contain sodalite.

3. The Southern Bahia Alkaline province

The Neoproterozoic alkaline rocks in southern Bahia (Fig. 1) were grouped together as the Southern Bahia Alkaline Province by Silva Filho et al. (1974). This province contains the Itabuna, Floresta Azul, Serra das Araras and Itarantim batholiths, a large number of stocks, such as those of Rio Pardo and Itaju do Colônia, and hundreds of dykes. The Itabuna batholith in the northern part of the province with a U–Pb age of 676 ± 5 Ma (Teixeira et al., 1997) is the youngest alkaline intrusion.

The larger intrusions of the SBAP are aligned NE–SW (Fig. 1C), and this is attributed to structural control of intrusion by deep faults which developed during tectonic episodes between the Paleoproterozoic and the Mesoproterozoic (Silva Filho et al., 1974; Mascarenhas and Garcia, 1987). The faults were reactivated during the Neoproterozoic after the intrusion of the alkaline plutons, and the effects of the reactivation are best seen in the northern intrusions of the SBAP, where they transect the syenitic bodies (Silva Filho et al., 1974; Corrêa-Gomes and Oliveira, 2002).

Contacts between the alkaline intrusions and basement rocks are sharp, and show that thermal and viscosity contrasts were large. It is inferred that the exposed magma chambers formed at depths between 6 and 8 km (Rosa et al., 2005a).

The southernmost part of the SBAP suffered the tectonic effects of the development of the Araçuaí mobile belt, and this is reflected by the northeastwards dislocation seen in the Itarantim batholith.

Intermediate miaskitic rocks predominate in the SBAP, and gabbro and diorite are more abundant in the northern intrusions than elsewhere. The available chemical compositions demonstrate the presence of two distinct trends, undersaturated and saturated in silica (Fig. 2A) that are believed to result from early fractionation of clinopyroxene and hornblende, respectively (Conceição et al., 1992). In both trends trace element compositions are those of anorogenic rocks (Fig. 2B). On the basis of the rare earth element (REE) patterns, and the absence of Nb and Ta anomalies in primitive mantle-normalized multi-element patterns, Menezes (2005) and Rosa et al. (2005a) found the signature of ocean island basalt (OIB) for the magmas of the southern part of the province.

4. Principal features of the dated alkaline intrusions

4.1. Floreta Azul alkaline complex

The complex is situated in the centre-northern part of the province (Fig. 1C). It has an NE–SW elongated shape, an area of about 200 km^2, and its contacts with the metamorphic host rocks are partly controlled by faults, although in some parts the regional structures are molded around the body. Fenites are locally present. The complex is formed by an eastern mainly granitic part, and a western syenitic part. The age of the granite is 696 ± 11 Ma, and of the accompanying diorite, 688 ± 2 Ma (Rosa et al., 2002), while the age of quartz syenites is 688 ± 10 Ma (Corrêa-Gomes and Oliveira, 2002), showing that the intrusions are contemporaneous.

The alkali granite intrusion is formed of granites with biotite and aegirine, which have between 10% and 30% of alkali diorite enclaves showing magmatic flow preferred orientations. The syenitic intrusion is composed of syenite with or without quartz in the margins, and foid-bearing syenites in the core. Sodalite syenite and blue sodalitite occur in centimetric to metric (2 m) bands, hosted by and in sharp contact with nepheline syenite. Zircon crystals up to 3 cm long are found in this facies. Cunha (2003) interpreted the structures of the blue sodalite rocks as the result of auto-metasomatism of nepheline syenite by a sodic peralkaline fluid rich in chlorine.

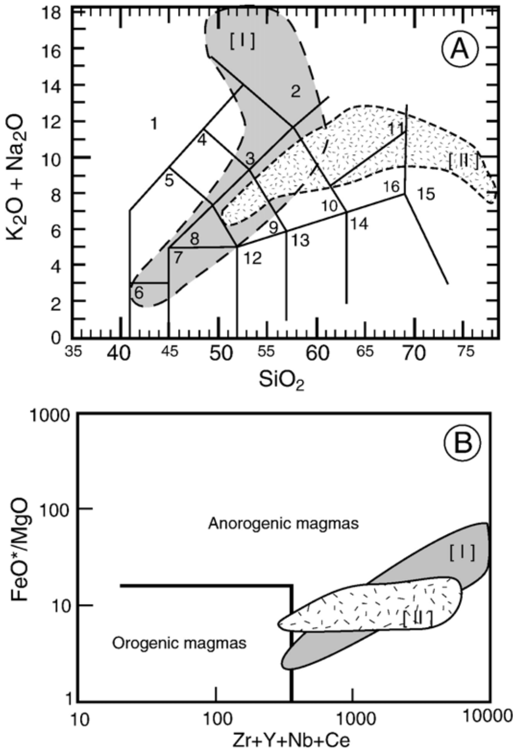

Fig. 2. TAS diagram with silica-undersaturated [I] and saturated [II] trends for rocks of the SBAP [A]. FeO*/Mgo vs. Zr+Nb+Ce+Y diagram (Whalen et al., 1987) with fields of orogenic and anorogenic magmas [B]. Data from Souto (1972), Fujimori (1978), Oliveira (2003), Cunha (2003), and Menezes (2005).

4.2. Itaju do Colônia stock

The stock is located in Hiassu Farm, about 20 km southwest of the Itaju do Colônia municipal district (Fig. 1C). The stock has an area of about 1 km^2, with a surface expression as a small convex hill formed by an ellipsoid intrusion with an NS-oriented major axis 1.4 km long. The stock intrudes Archaean–Paleoproterozoic granulites of the Itabuna Belt. Contacts with the metamorphic host rocks are sharp, and are often occupied by dykes or pegmatite masses of syenite.

At present, the many mining faces used to extract Blue Bahia dimension stone allow a good evaluation of the distribution of the rocks which compose the stock. It is mainly composed of litchfieldite in which the nepheline is predominantly green. In the southeastern area a sodalitite layer with deep blue colour makes sharp contact with the sodalite litchfieldite, and is used for making jewelry.

The litchfieldites are usually isotropic, though shear zones are present locally. Rounded dark clots are composed of biotite, aegirine, potassian taramite, sulphide minerals and calcite. Discontinuous thin (<2 cm wide) layers of aegirine are thought to be products of percolation of late fluids along fractures (Rosa et al., 2005b). Very coarse pegmatite masses are common and some contain large albite crystals up to 20 cm long, while nepheline crystals sometimes attain a length of 1 m.

The sodalite litchfieldites are medium-grained. Albite prisms are euhedral to subhedral and form angular or triangular arrangements with the interstitial spaces filled by sodalite, titanite, microcline, aegirine and calcite (Fujimori, 1978; Rosa et al., 2005b). The textural relationships show that sodalite crystallized directly from the magma after nepheline, and was followed by microcline, titanite, calcite and aegirine. Magnetite, ilmenite, sulphide minerals and analcime occur sporadically, and cancrinite and paragonite are late-formed minerals.

4.3. Rio Pardo stock

This stock which crops out over about 46 km^2 was identified by Souto (1972) and mapped in detail by Menezes (2005). Its polygonal form is due to faults which define its contact with granulite, gneiss–migmatite, quartz syenites of the Serra das Araras syenite massif, and gabbros of the Rio Pardo gabbro–anorthosite complex. The stock is mainly composed of nepheline-bearing syenite and nepheline syenite. A whole rock Rb–Sr isochron age of 734±26 Ma was obtained for the latter (Menezes, 2005), making this stock the oldest intrusion of the SBAP.

The nepheline-bearing syenites are grayish-white medium to coarse-grained rocks with biotite agglomerates which confer the grey tone and also define the magmatic flow foliation. The nepheline syenites are greenish grey, fine-grained to pegmatitic. Deep green nepheline crystals are interstitial to perthitic orthoclase. Biotite is the main mafic mineral, together with subordinate taramite and aegirine. Blue sodalite is sometimes present, and the accessory minerals are titanite, apatite, calcite, magnetite and sometimes zircon. The distribution and grain size of sodalite syenites are varied, but they are intimately associated with pegmatitic nepheline syenite with which the contacts are gradual. Biotite is the dominant mafic mineral, and the accessory minerals are usually titanite, calcite, and more rarely magnetite.

4.4. Itarantim batholith

This batholith whose area is about 220 km^2 is located in the extreme southern part of the SBAP (Fig. 1C). It was identified by Silva Filho et al. (1974), and was mapped by Oliveira (2003). The batholith is composed of two main facies, aegirine nepheline syenites to the north and biotite nepheline syenites to the south, with gradational contacts between the two. A whole rock Rb–Sr isochron age of 727±49 Ma was obtained for these rocks (Oliveira, 2003). Basic, phonolitic and pegmatitic dykes are sometimes present, the latter including nephelinolite and zircon sodalite nepheline syenite. The contact with the gneiss–migmatite host rocks is through a fenitizated aureole.

The sodalite syenite occurs as a 3 m wide, medium to coarse-grained pegmatite dyke cutting biotite nepheline syenite. The sodalite content reaches 40%, and its homogeneous distribution is responsible for its commercial value. The dyke is mainly composed of orthoclase perthite, albite antiperthite, sodalite, nepheline and biotite, with aegirine, cancrinite, calcite, zircon, fluorite and opaque minerals as accessories. The intrusion of the dyke caused important metasomatic transformations in the nepheline syenite host rocks. First, sodalite replaced nepheline, then alkali feldspars are partially replaced by sodalite. Later in the petrogenetic sequence, cancrinite and calcite sometimes replace sodalite (Rosa et al., 2005a). In the pegmatitic masses, zircon crystals whose size attains 4 cm crystallized after the perthitic alkali feldspar but before biotite, albite, sodalite and the opaque minerals. Fractures which cut the crystals have no infilling and are therefore late-formed.

5. Petrological constraints of blue sodalite in the SBAP

Sodalite is one of the few rock-forming minerals which contain chlorine as an essential component. The experimental studies of Wellman (1970) and Sharp et al. (1989) suggest two main processes for its formation, the fractional crystallization of highly-evolved silica-undersaturated liquids, and metasomatism.

Petrological studies of the Itarantim batholith (Oliveira, 2003), the Floresta Azul alkaline complex (Cunha, 2003) and the Rio Pardo (Menezes, 2005) and Itaju do Colônia (Fujimori, 1978; Rosa et al., 2005b) stocks where Blue Bahia is mined show that the magmatic and metasomatic processes are both involved.

Magmatic sodalite was found in dykes cutting the Itarantim batholith and in litchfieldite of the Itaju do Colônia stock. The sodalite crystals are disseminated and interstitial to perthitic and antipertitic alkali feldspar crystals and are associated with calcite and cancrinite formed by destabilization of nepheline. Metasomatic sodalite is found in syenite of the Floresta Azul alkaline complex and in both stocks. It occurs as discontinuous 10 m long bands with sharp contacts with host pegmatitic nepheline syenite, and contains calcite as an accessory mineral in the form of veinlets or thin dykes. The sodalite syenite bands have granular textures and the sodalite aggregates often contain relicts of nepheline and albite with replacement textures. The metasomatic process is also responsible for the formation of magnetite, calcite, pyrite, biotite, cancrinite and sometimes fluorite.

6. Geochronology

6.1. Analytical techniques and samples

The Pb–Pb evaporation ages of single zircon fragments, and U–Pb isotope dilution ages of titanite fragments were undertaken at the Isotope Geology Laboratory (Pará-Iso) of the Federal University of Pará, Belém, Brazil. All the U–Pb ages were calculated with a 2σ (95%) precision using ISOPLOT (Ludwig, 2001). Details of chemical separations and analytical methods are given in the Appendix.

Table 1
Analytical results of the Pb–Pb method for zircon fragments from the Floresta Azul complex and the Itarantim batholith

Crystal	Evaporation T (°C)	Ratios	$^{204}Pb/^{206}Pb$	±2σ	$[^{207}Pb/^{206}Pb]_C$	±2σ	Age	±2σ
Floresta Azul complex (Sample 2098)								
3	1500	22/22	0.000080	24	0.06250	39	692	13
6	1450	08/08	0.000048	4	0.06261	16	695	6
7	1450	16/24	0.000051	16	0.06253	33	693	11
8	1500	3240	0.000041	1	0.06267	14	697	5
						Mean Age: 696±3 Ma		
Itarantim batholith (Sample 2034)								
2	1600	30/34	0,000051	15	0.06339	16	721	5
6	1450	32/40	0,000382	7	0.06326	38	717	13
8	1620	12/34	0,000371	7	0.06957	32	727	11
						Mean Age: 722±5 Ma		

$[^{207}Pb/^{206}Pb]_c$ = ratio correct for common Pb.

Pb–Pb determinations of zircon from the Floresta Azul complex and the Itarantim batholith were undertaken on fragments less than 0.6 mm long that were broken and hand-picked from the 1 mm to 4 cm long natural crystals. These crystals have mainly D-type morphologies (Pupin, 1980), compatible with the alkaline nature of the rocks.

Since no zircon was observed in thin sections from the Itaju do Colônia and Rio Pardo stocks, U–Pb analyses were made on titanite which occur in aggregates with diameters up to 3 cm. Whole rock samples were broken and ground to allow concentration of titanite fragments which were hand-picked using a stereomicroscope to select the best grains for isotopic analysis.

6.2. Results

Sample 2098 (UTM coordinates 415328-8345604) from the Floresta Azul complex is a blue biotite sodalite syenite which contained aggregates of subhedral zircon crystals up to 3 cm long. A population with reddish-brown, prisms, 1 to 2 cm long, with few inclusions and fractures, yielded four unfractured and inclusion-poor fragments. An age of 696±3 Ma (MSWD=0.39) was obtained (Table 1, Fig. 3A).

Sample 2634 (UTM coordinates 416067 - 8304018) from the Itaju do Colônia stock is a coarse-grained blue sodalite litchfieldite which has aggregates of titanite crystals up to 2 cm. The analysed fragments were brown, transparent, fractures and inclusion free. Three groups of fragments yielded a concordia age of 732±8 Ma (Table 2, MSWD=0.82, Fig. 4A).

Sodalite syenite from the Rio Pardo stock (sample 2144, UTM coordinates 410806-8276964) yielded light brown titanite fragments, fractures and inclusion free, five of which yielded an age of 714±8 Ma (MSWD=0.04, Table 2, Fig. 3B).

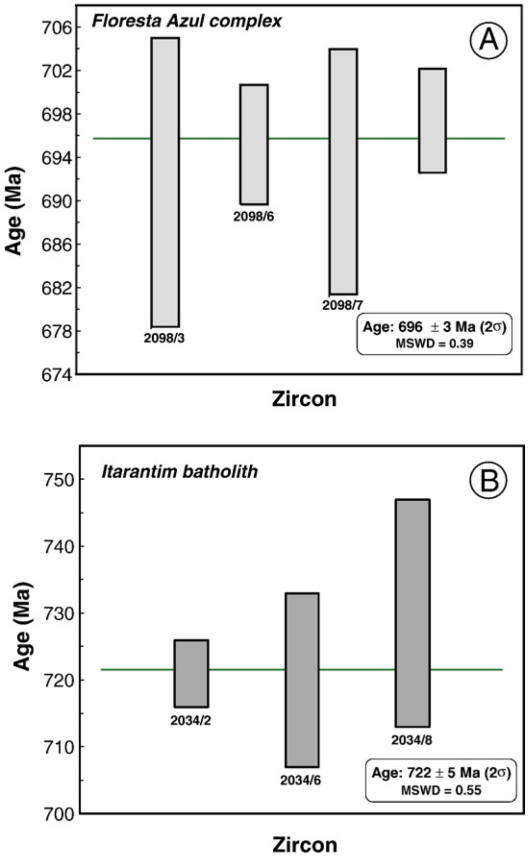

Fig. 3. U–Pb ages of zircon crystals determined by the Pb–Pb evaporation method. [A] Floresta Azul complex; [B] Itarantim batholith.

Table 2
U–Pb data for titanite from the Itaju do Colônia and Rio Pardo stocks

Titanite	Weight	U	Pb	$^{206}Pb/^{204}Pb$	$^{207}Pb^{*}/^{235}U$	$^{206}Pb^{*}/^{238}U$	$^{207}Pb^{*}/^{206}Pb$	$^{207}Pb/^{206}Pb$
(Concentrate)	(g)	(ppm)	(ppm)	(Corrected)	(*Radiogenic)	(*Radiogenic)	(*Radiogenic)	Age (Ma)
Itaju do Colônia stock (sample 2634)								
01	0.001740	788.6	71.2	483.928	0.696 ± 3.510	0.080 ± 3.110	0.062975 ± 1.51	707.4
02	0.002047	749.1	57.2	1439.53	0.630 ± 5.280	0.073 ± 5.270	0.062479 ± 0.345	690.5
03	0.000909	416.8	34.1	1668.01	0.650 ± 1.580	0.075 ± 1.390	0.062467 ± 0.711	690.1
04	0.001668	422.5	36.0	1174.62	0.661 ± 0.519	0.076 ± 0.267	0.062716 ± 0.413	698.6
05	0.000146	333.1	41.5	455.032	0.912 ± 0.835	0.104 ± 0.791	0.063413 ± 0.261	722.1
Rio Pardo stock (sample 2144)								
01	0.0023219	14.4	3.9	99.0238	0.69213 ± 15.400	0.07820 ± 1.300	0.064190 ± 14.2	747.9
03	0.0021688	13.6	3.5	115.185	0.70136 ± 0.950	0.08044 ± 0.868	0.063238 ± 0.4	716.2
09	0.0009145	195.2	4.2	103.395	0.05959 ± 1.650	0.00661 ± 1.620	0.065369 ± 0.3	786.2

The Pb–Pb age of 722 ± 5 Ma (MSWD = 0.55) for the Itaratim batholith (sample 2034, UTM coordinates 379138-8251288) was obtained for 0.2 to 0.5 mm inclusion-free fragments of long, translucent deep red brown zircon prisms from a pegmatitic sodalite nepheline syenite (Table 1, Fig. 4B).

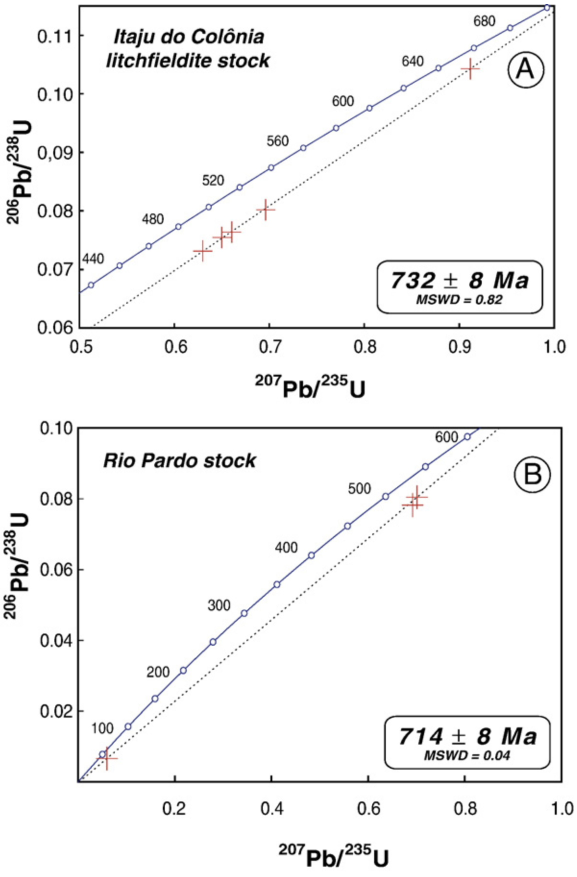

Fig. 4. U–Pb diagram for titanite concentrates. [A] Itaju do Colônia stock; [B] Rio Pardo stock.

7. Discussion

7.1. Tectonic significance of the anorogenic alkaline magmatism of the SBAP

Although blue sodalite syenite is rare, occurrences are known from the Proterozoic, represented by the 1120–1140 Ma Swartbooisdrif deposit in Namibia (Drüpprel et al., 2005) to the Mesozoic, represented by the 98–100 Ma Cerro Sapo deposit in Bolivia (Schultz et al., 2004). Independent of their ages deposits are always associated with rifts. In the São Francisco craton, evidence for tensional episodes during the early stages of the Brasiliano orogeny is present in the northern part of the SBAP in the form of abundant tholeiitic fissural magmatism at about 1 Ga (D'Agrella Filho et al., 1990; René et al., 1990). South of the province in the Araçuaí belt, anorogenic magmatism at 875 Ma (Silva et al., 2004) and 816 Ma ophiolites (Mantesso Neto et al., 2004) have been identified which, according to Pedrosa Soares et al. (2001), were associated with a rifting stage which preceded the orogeny. Almeida et al. (2000) inferred that the Brasiliano collisions between 0.96 and 0.54 Ga was diachronic in the different structural provinces of South America. In the São Francisco craton the event involved closure of marginal basins which generated the Neoproterozoic fold belts which surround the craton, and which have complex histories (Mantesso Neto et al., 2004).

In the Neoproterozoic the Adamastor–Brazilide ocean (Dalziel, 1997) was formed during the break-up of the Rodinia supercontinent which started in the São Francisco–Congo region around 1.0–0.9 Ga (Brito-Neves et al., 1999). In the western Congo craton, a continuation of the Araçuaí belt, evidence for the tensional phase is found in the presence of alkaline magmatism in the form of plutonic activity at 999 ± 7 Ma, volcanism between 920 and 912 Ma (Tack et al., 2001), and carbonatite formation between 940 and 780 Ma (Kampunzu et al., 1998), or 837±60 Ma (Buhn et al., 2001).

The geochronological data for the SBAP show that the alkaline magmatism was active during at least 58 Ma between 734 and 676 Ma in a tectonically stable environment in the southern part of the São Francisco craton, although structural control determined the intrusion of the bodies along a NE–SW lineament. On the African side, structures with this orientation and similar ages are attributed to rift systems (e.g. Sangha: Alvarez and Maurin, 1991).

Geotectonic models previously proposed to explain the Neoproterozoic evolution of this part of the São Francisco craton placed the rifting in the time interval between 1.0 and 0.8 Ga (Uhlein et al., 1998; Pedrosa Soares et al., 2001; Silva et al., 2004). The SBAP magmatism was not included in these discussions, probably due to the uncertainty as to the ages of intrusions with available values between 760 and 490 Ma. The precise ages obtained in this study define the extension of the pre-Araçuaí rifting to around 700 Ma, with the SBAP alkaline magmatism representing the final phase as a tensional event which started in Africa around 900 Ma.

7.2. Ages of the deposits and implications for the genesis of blue sodalite

The studied alkaline intrusions are distributed within an area of about 6500 km^2, about 80% of the total area of the SBAP, and the geochemical data points to an anorogenic regime for magmas derived from a source with OIB isotopic characteristics (Menezes, 2005; Rosa et al., 2005a).

The geochronological data for the economic deposits show that blue sodalite syenites were produced during an interval of at least 36 Ma, and the ages of the blue rocks and the nepheline syenite host rocks are similar (Table 3), demonstrating that the genesis of the sodalite is part of the processes which occurred during crystallization. In this way, the sodalite crystallize directly from the magma or by fluid interaction.

Table 3
Ages of sodalite syenite and host rocks from the SBAP

	Sodalite syenite (Ma)	Host rocks (Ma)	Analytical technique	Source
Floresta Azul complex	696±3	696±11	Pb–Pb (evaporation)	Rosa et al. (2002)
Rio Pardo stock	714±8	734±26	Rb–Sr (whole rock)	Menezes (2005)
Itarantim batholith	722±5	727±49	Rb–Sr (whole rock)	Oliveira (2003)

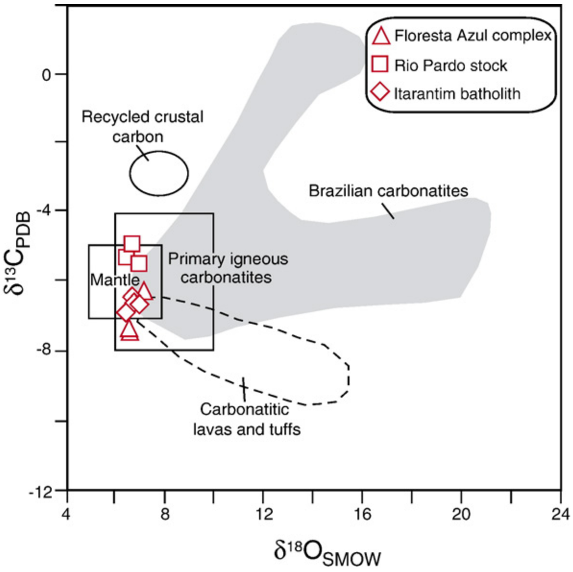

Fig. 5. Isotopic compositions of calcite concentrates from the SBAP in the $\delta^{18}O_{SMOW}$ versus $\delta^{13}C_{PDB}$ diagram. Mantle and primary carbonatite fields from Hoefs (1987), Nelson et al. (1988) and Deines (1989). Other fields for reference from Schultz et al. (2004).

Petrological studies of the SBAP (Souto, 1972; Fujimori, 1978; Cunha, 2003; Oliveira, 2003; Menezes, 2005) show that the crystallization of blue sodalite is accompanied by that of calcite which occurs as aggregates, veinlets or thin dykes (e.g. in the Rio Pardo stock: Menezes, 2005). Isotopic analyses of C and O in calcite from different intrusions show that the $\delta^{13}C_{PDB}$ and $\delta^{16}O_{SMOW}$ values fall in the domain of primary carbonatites (Rosa et al., 2005b; Fig. 5). This shows that the evolution of the alkaline magmas of the SBAP occurred in a closed system, since the most differentiated rocks retain a mantle signature. The presence of magmatic calcite in blue sodalite syenite in the SBAP is not an isolated case, having been described also in the Namibian (Drüppel et al., 2005, Bolivian (Schultz et al., 2004) and Argentinian (Rubiolo, 2005) occurrences in which this rock is associated with carbonatites.

8. Summary

The Southern Bahia Alkaline Province hosts the only economic deposits of blue sodalite syenite in Brazil. This study establishes that the blue sodalite syenites were intruded between 696 and 732 Ma. The petrological and geochronological data show that the blue syenites are generated by two processes, magmatic crystallization and metasomatism. The anorogenic alkaline magmatism of the province appears to have occurred in an extensional environment during rifting of the southern part of the Sao Francisco craton. This extension persisted until about 700 Ma.

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Appendix A. U–Pb and Pb–Pb methods

Titanite is placed in ethanol in an ultrasonic bath for 5 min, followed by three washings with deionized water. A few drops of 2.5N HCl are added, and the fragments are heated on a hot plate for five minutes. After a second washing with deionized water, three to six fragments are weighed together with the PARÁ ^{205}U/^{235}U spike in a PFA Teflon Savilex® micro-capsule. After weighing, three drops of tri-distilled concentrated HF are added, the micro-capsules are placed in a 120 ml Parr bomb, and the bombs are heated in stove for 12 h at 200 °C. After removal and cooling, the solutions are evaporated, three more drops of 2.5N HCl are added, and another digestion at 200 °C for twelve hours is made. The chemical separation of the solutions is made on a Savilex® column containing 20–25 μl of a 1:3 mixture of Eichrom® Sr-Spec and TRU-Spec for the collection of U and Pb. Isotopic ratios and concentrations were determined by measurement on a Finnegan MAT 262 mass spectrometer.

The Pb–Pb evaporation of single zircon fragments followed the procedure introduced by Köber (1987). The measurements were made on a Finnegan MAT 262 mass spectrometer using an ion counter. Ten scans form a block of readings. Ages are calculated from the ^{207}Pb/^{206} ratios of the blocks for each evaporation stage, and the results are presented in diagrams of age in Ma for each analysed grain.

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