DOI: 10.5327/Z2317-48892013000300005

ARTICLE

Grenvillian age magmatism in the Southern Espinhaço Range (Minas Gerais): evidence from U-Pb zircon ages

Magmatismo de idade grenvilleana na Serra do Espinhaço Meridional (Minas Gerais): evidências baseadas em idades U/Pb em zircão

Mario Luiz de Sá Carneiro Chaves[1]*, Márcio Célio Rodrigues da Silva[2], Ricardo Scholz[3], Marly Babinski[4]

ABSTRACT: This paper describes the first *in situ* occurrence of a volcanic rock with maximum deposition age of *ca.* 1.16 Ga suggesting a Grenvillian (~ 1.4 – 1.0 Ga) magmatic event in the Southern Espinhaço Range. Sample Vul-1A is intrusive within the Archean Basement Complex, and is characterized by a brecciated structure, with clasts of schists, banded iron formations (BIFs), volcanic and granitic rocks, in a very fine to medium-grained matrix. Petrographically, it has a basic nature with alkaline tendency, defined as a basaltic trachyandesite to trachybasalt, with volcaniclastic aspects. Zircons recovered from the matrix of this rock showed three types of ages: Archean ages (mainly between 2.9 – 2.7 Ga), Paleoproterozoic ages (2.2 – 1.8 Ga), and the most important, Grenvillian ages (1.20 – 1.16). Geochemical data showed that this unit is not similar of the post-Espinhaço meta-basic rocks (Pedro Lessa Suite), dated at 1.0 – 0.9 Ga. If the occurrence of an igneous rock of that age is confirmed, with such facies aspect, it reinforces the idea that similar magmatic processes possibly of explosive type occurred during the last syn-rift phase of the Espinhaço basin evolution. Our geochronological data may have identified the possible source of the Grenvillian detrital zircons from the Sopa-Brumadinho Formation, and suggest that these volcanic processes were coeval and recurrent during the sedimentation of this unit.

KEYWORDS: LA-ICP-MS ages; detrital zircons; Grenvillian magmatism.

RESUMO: *Este trabalho descreve a primeira possível ocorrência in situ de uma rocha vulcânica datada no período Grenvilleano (~ 1,4 – 1,0 Ga) na Serra do Espinhaço Meridional, com idade máxima de deposição em ca. 1,16 Ga. A amostra Vul-1A, intrusiva no Complexo Basal arqueano, possui estrutura brechoide, formada por clastos de xistos, formações ferríferas (FFs), rochas vulcânicas e granitoides, em matriz vulcânica muito fina a média, petrograficamente de natureza básica com tendência alcalina, definida como um traquiandesito basáltico a traquibasalto, com características vulcanoclásticas. Zircões retirados da matriz dessa rocha indicaram três intervalos de idades característicos: arqueana (principalmente entre 2,9 – 2,7 Ga), paleoproterozoicas (2,2 – 1,8 Ga) e, as mais importantes, grenvilleanas (1,20 – 1,16 Ga). Em relação à sua assinatura geoquímica, ela não mostra semelhança com as rochas metabásicas pós-Espinhaço (Suíte Pedro Lessa), datadas entre 1,0 – 0,9 Ga. Se confirmada a ocorrência de uma rocha ígnea dessa idade, e com tal faciologia, reforça-se a ideia de que processos magmáticos semelhantes possivelmente de natureza explosiva, acompanharam a evolução da bacia Espinhaço durante seu período sinrifte final. Os dados geocronológicos obtidos podem ter identificado a possível fonte dos zircões detríticos grenvilleanos da Formação Sopa-Brumadinho e sugerem que tais processos vulcânicos foram contemporâneos e recorrentes durante a sedimentação dessa unidade.*

PALAVRAS-CHAVE: *idades LA-ICP-MS; zircões detríticos; magmatismo grenvilleano.*

[1]Instituto de Geociências, Universidade Federal de Minas Gerais - UFMG; CNPq Research Fellow, Belo Horizonte (MG), Brasil. *E-mail: mchaves@ufmg.br*

[2]Programa de Pós-Graduação em Geologia, Instituto de Geociências, Universidade Federal de Minas Gerais - UFMG; GEOMIL Ltda., Belo Horizonte (MG), Brasil. *E-mail: celiogeo@gmail.com*

[3]Departamento de Geologia, Escola de Minas, Universidade Federal de Ouro Preto - UFOP, Ouro Preto (MG), Brasil. *E-mail: r_scholz_br@yahoo.com*

[4]Instituto de Geociências, Universidade de São Paulo - USP; CNPq Research Fellow, São Paulo (SP), Brasil. *E-mail: babinski@usp.br*

*Corresponding author

Manuscrito ID 29853. **Recebido em:** 09/05/2013. **Aprovado em:** 24/07/2013.

INTRODUCTION

In Southern Espinhaço Range, the main magmatic event of the Espinhaço Supergroup is expressed by acid volcanic rocks in the Conceição do Mato Dentro region and rocks of unknown protolith, known as hematite phyllites, which are found near the city of Diamantina. The 1.75 – 1.71 Ga age of these rocks (Brito Neves *et al.* 1979, Machado *et al.* 1989, Dussin 1994) and their location at the base of the sedimentary succession are applied to define the initial opening stage of the Espinhaço basin. The minimum depositional age of deposition for the Espinhaço Supergroup is constrained by intrusions of meta-basic rocks, with ages from 1.0 to 0.9 Ga (Machado *et al.* 1989) that do not crosscut the lithotypes of the upper Macaúbas Group.

Geochronological data on detrital zircon from siliciclastic sequences of the Espinhaço Supergroup have identified the presence of a younger population of grains, dated at 1.2 to 1.0 Ga (Chemale Jr. *et al.* 2012, Santos *et al.* 2013, Chaves *et al.* 2013). The new data were responsible for reassessment of the age of an important portion of these deposits and suggest the occurrence of a new magmatic event, until unknown, within the tectonic period worldwide described as "Grenville".

Systematic detailed geological mapping and mineral exploration work oriented to the banded iron formation (BIF) of the Pedro Pereira Formation, in the southern region of Gouveia (Chaves *et al.* 2012), identified a volcaniclastic rock hosted by granitoid rocks. The geological and geochemical study of this hybrid rock, as well as U-Pb geochronological data obtained of detrital (and possibly magmatic) zircons, constitute the aims of this work.

REGIONAL GEOLOGY

Along its southern segment, the Espinhaço Range extends from the northern tip of the Square Quadrangle (Quadrilátero Ferrífero) to the north of Diamantina city, corresponding to a large N-S trending anticlinorium mainly formed by a thick succession of siliciclastic rocks, the Espinhaço Supergroup (Fig. 1).

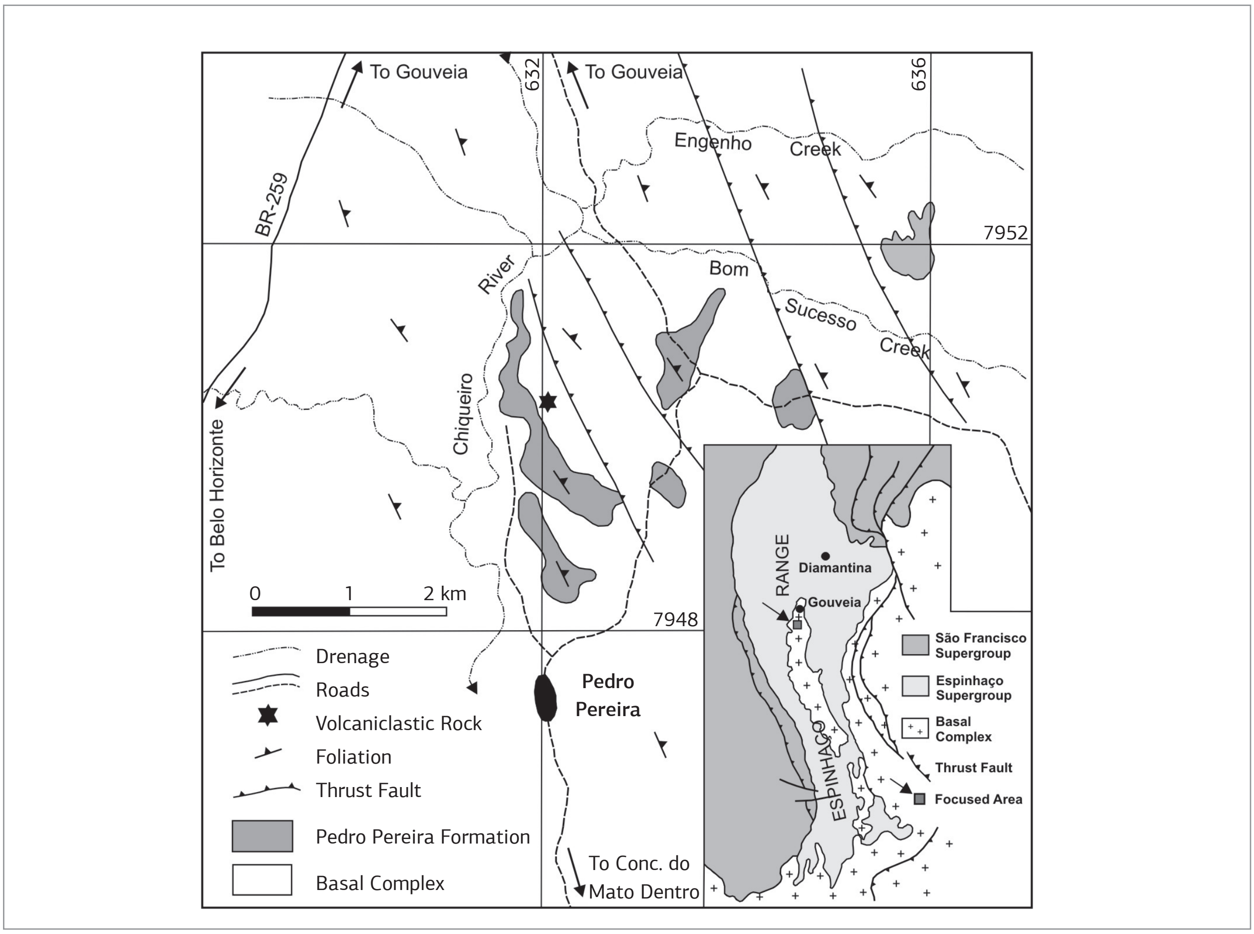

Figure 1. Simplified geological map of the Pedro Pereira region, south of Gouveia, showing the distribution of Pedro Pereira Formation (Costa Sena Group) embedded in the granitoid rocks of the Basal Complex (after Carvalho 1982). In the insert (right), the studied area is shown in the context of the Southern Espinhaço Range.

This last sequence includes a thick package of siliciclastic rocks, deposited from fluvial, aeolian to marine environments, with minor intercalations of metavolcanic rocks but cut by a number of dykes of distinct ages (Brito-Neves *et al.* 1979, Fogaça *et al.* 1984, Machado *et al.* 1989, Corrêa-Gomes & Oliveira 2000, Almeida-Abreu & Renger 2002). The bi-modal (mafic-felsic) metavolcanic rocks and related anorogenic granites (Borrachudos Suite), together with evidence from the sedimentary pile, suggest continental rift setting for the Espinhaço Supergroup (Dussin & Dussin 1995, Brito-Neves *et al.* 1995, Alkmim & Martins-Neto 2012). Recently, new U-Pb geochronological data suggest the superposition of two continental rift basins in the Espinhaço Supergroup in its southern segment (Chemale-Junior *et al.* 2012, Santos *et al.* 2013). Accordingly, the oldest rift (Espinhaço I), Statherian in age (*ca.* 1.75 Ma), comprises the two basal units (Bandeirinha and São João da Chapada formations) which are covered by the thickest succession found along the range, corresponding to the Sopa-Brumadinho to Rio Pardo Grande formations, which represents the youngest rift basin (Espinhaço III). The second rift stage (Espinhaço II, *ca.* 1.5 Ga) was not yet found in the Southern Espinhaço range, but is well known in the Northern Espinhaço-Chapada Diamantina system (Danderfer *et al.* 2009). Espinhaço III was followed by the first rifting event that formed the Macaúbas basin, a Tonian continental rift starting around 900 Ma (Pedrosa-Soares *et al.* 2011, Babinski *et al.* 2012).

It seems that no significant orogenic event involved the Espinhaço Supergroup in Mesoproterozoic time, as no magmatic arc and/or ophiolites are found associated with it. Nevertheless, some structural features, like Appalachian-type folding that affected the Espinhaço-Chapada Diamantina system in the São Francisco Craton, may be related to some kind of far-distance tectonic influence of the Grenvillian Orogeny (Brito-Neves *et al.* 1995, Zalán & Silva 2007, Cordani *et al.* 2010). However, the large-scale importance of within-plate events, like extensional magmatic events, related to the Grenvillian time has been stressed by some authors (Brito-Neves *et al.* 1995, Cordani *et al.* 2010).

On the other hand, the Southern Espinhaço Supergroup shows striking tectonic-metamorphic features imposed by the Brasiliano Orogeny, along the Araçuaí fold-and-thrust belt (Almeida 1977, Alkmim *et al.* 2006). This orogeny caused a regional thrust stacking along the eastern border of the São Francisco Craton, with a remarkable stratigraphic inversion that shows the Espinhaço Supergroup tectonically carried onto the Macaúbas and Bambuí groups. In addition, the basement was involved in the Brasiliano orogeny, giving rise to extensive development of mylonitic rocks after Archean gneisses and granites (Cruz *et al.* 2005).

The basement of the Southern Espinhaço Supergroup, exposed in the central portion of the range from Gouveia to Conceição do Mato Dentro, mostly includes Archean granites and gneisses (Brito Neves *et al.* 1979, Machado *et al.* 1989). Narrow bands of schist, tectonically intercalated within basement granitic rocks, have been a subject of controversy. Hoffmann (1980, 1983) designated these schists as Costa Sena Group, composed by quartz-mica schists, quartz schists, quartzites and BIFs, with intercalations of meta-basic and meta-ultrabasic rocks. Carvalho (1982) included part of these rocks in the Volcano-Sedimentary Sequence of Pedro Pereira, which was redefined as Pedro Pereira Group by Fogaça *et al.* (1984), placed at the base of the Rio Paraúna Supergroup, with the Costa Sena Group in its upper portion. However, several authors have pointed out that these schists are mylonitic outcomes from Archean granitic rocks, formed by the Brasiliano ductile deformation that affected both the basement and the Supergroup Espinhaço in the focused region (Carvalho 1982, Dossin *et al.* 1990, Cruz *et al.* 2005).

ROCK OCCURRENCE SITE GEOLOGY

The studied area was recently investigated for iron mineralization contained in BIFs of the Pedro Pereira Formation (Chaves *et al.* 2012). During the fieldwork of this research, a brecciated rock with an apparent linear shape was identified, showing an E-W trend, and minimal exposed dimensions of 50 m long and 6 m wide, hosted by the Archean Basement Complex. Due to the geographical proximity with the clastic-chemical meta-sediments of the Pedro Pereira Formation, this body had been formerly related to it (Carvalho 1982). The host rocks in the area are intensely foliated in a NW-SE direction, with prominent dip to NE (Fig. 1).

The rock shows brecciated structure, very fine to medium matrix, intense green color, without apparent deformation. Most clasts exhibit sizes between 5 and 20 cm, with some bigger ones of 25 – 35 cm, and include granite, mica schist, BIFs, basic volcanic rocks, and quartz, mostly angular to sub-angular, which suggests its short transport from the source area. The clast-matrix ratio varies between 40 and 60%. The framework of this rock is totally chaotic, without grading or preferred orientation of clasts or its matrix (Fig. 2).

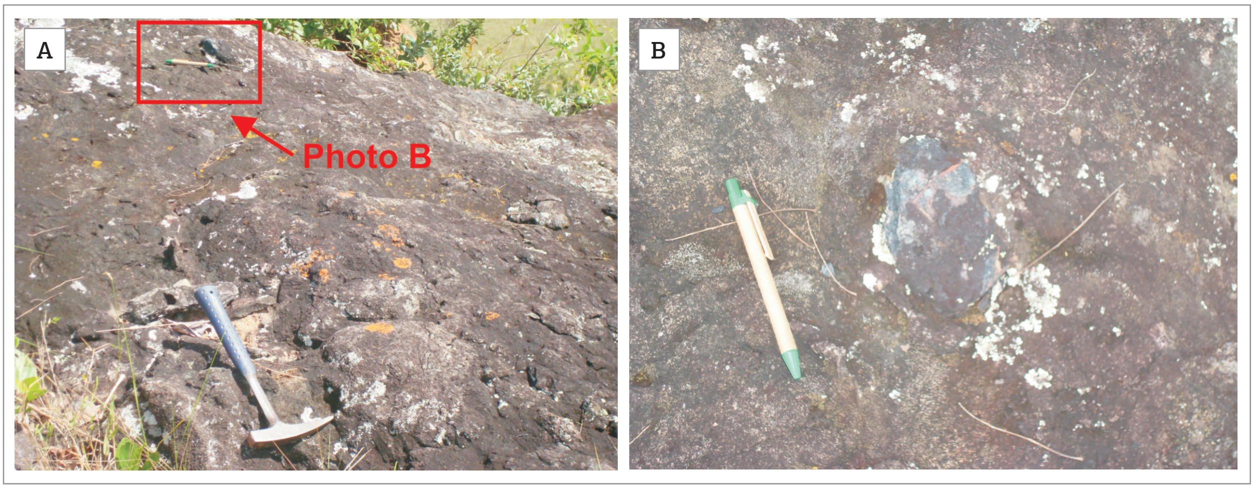

Figure 2. (A) General aspect of the brecciated volcaniclastic rock near the Pedro Pereira village, and (B) a detail of a sub-angular clast of banded iron formation.

Petrographic description

Thin sections of three poor matrix fragments, sampled in different areas of the body, allow to characterize a porphyritic granular texture, with plagioclase, biotite and epidote (> 20%), and minor amounts (1 – 10%) of carbonate, quartz, chlorite, titanite and opaque minerals, besides rare zircon, apatite and orthoclase.

The rock is in general homogeneous, fine-grained to locally medium-grained (size of crystals ranging from 0.01 to 2.80 mm), showing fine to very fine abundant matrix composed by crystal aggregates of epidote associated with phyllosilicates (biotite and chlorite). In the matrix can be found: (a) semi-decussate phenocrysts of plagioclase (tabular crystals), (b) phenocrysts of quartz and locally K-feldspar, (c) sub-angular fragments, of milimetric to centimetric size, of gabbro/diorite and granitoid rocks, and (d) amygdales filled by carbonate, biotite, chlorite, quartz, epidote, and opaque minerals (Fig. 3).

The plagioclase is predominantly albite, occurring in subhedral to euhedral crystals, sometimes twinned according albite/Carlsbad and pericline laws. Some crystals show tensional fractures, deformed twins, myrmekites (rare), and incipient to moderate saussuritization. Altered orthoclase occurs in subhedral phenocrysts with perthitic structure (cords). Green biotite changes to chlorite. Crystals of apatite, zircon and titanite are scattered through the sample. Opaque minerals, sometimes poikilitics, constitute subhedral to euhedral crystals and are also randomly scattered through the sample.

Rock composition was statically modified recalibrated by percolation of hydrothermal fluids, indicated by lack of orientation of the crystals. In the process, transformations of brown biotite (primary) to green biotite and later to epidote/chlorite are observed, and small fillets of stilpnomelane (final phase) also can be verified. This rock can be petrographically classified as a volcanic basic to intermediate, containing fragments of host rocks, which confer to it a characteristic, brecciated structure.

Geochemistry

Although only five samples were analyzed (from the same outcrop), the results allow us to suggest a tentative geochemical classification of the rock. Samples Vul-01, Vul-03, Vul-04 and Vul-05 are consistent with the micro-petrographic classification (Tabs. 1 and 2; Figs. 4 and 5). However, sample Vul-02 diverged strongly from the others, and will be discarded in the following discussion.

Based on the TAS classification diagrams, and considering a low degree of metamorphic alteration and weathering, the samples located in the field corresponding to basaltic trachyandesite to trachybasalt (Le Bas *et al.* 1986, Fig. 4A). The alkaline character of this rock is supported by the Irvine & Baragar (1971) diagram (Fig. 4B). In these diagrams, we have added data from a grouping of meta-basic rocks of post Espinhaço age, known as "Pedro Lessa Suite" (Hoppe *et al.* 2003) for comparison. They represent two different types of volcanisms that are not related.

Concentration sum values of the rare earth elements (REEs) range from 266.21 ppm (Vul-05) to 368.54 ppm (Vul-01). The distribution pattern of these elements presents remarkable enrichment of light REEs (La-Eu), with the relationship between Σ light REEs /Σ heavy REEs ranging from 6.8 to 7.8 (Tab. 1). The spidergram of Haskin *et al.* (1968) indicates the strong fractionation between light REEs and heavy REEs (Fig. 5). The degree of fractionation between light REEs and heavy REEs (Haskin *et al.* 1968), shows that the samples have values greater than one, corresponding to the relative enrichment of light REEs (Tab. 2). The observed pattern of the REEs is common for basic rocks (e.g. Cox *et al.* 1979).

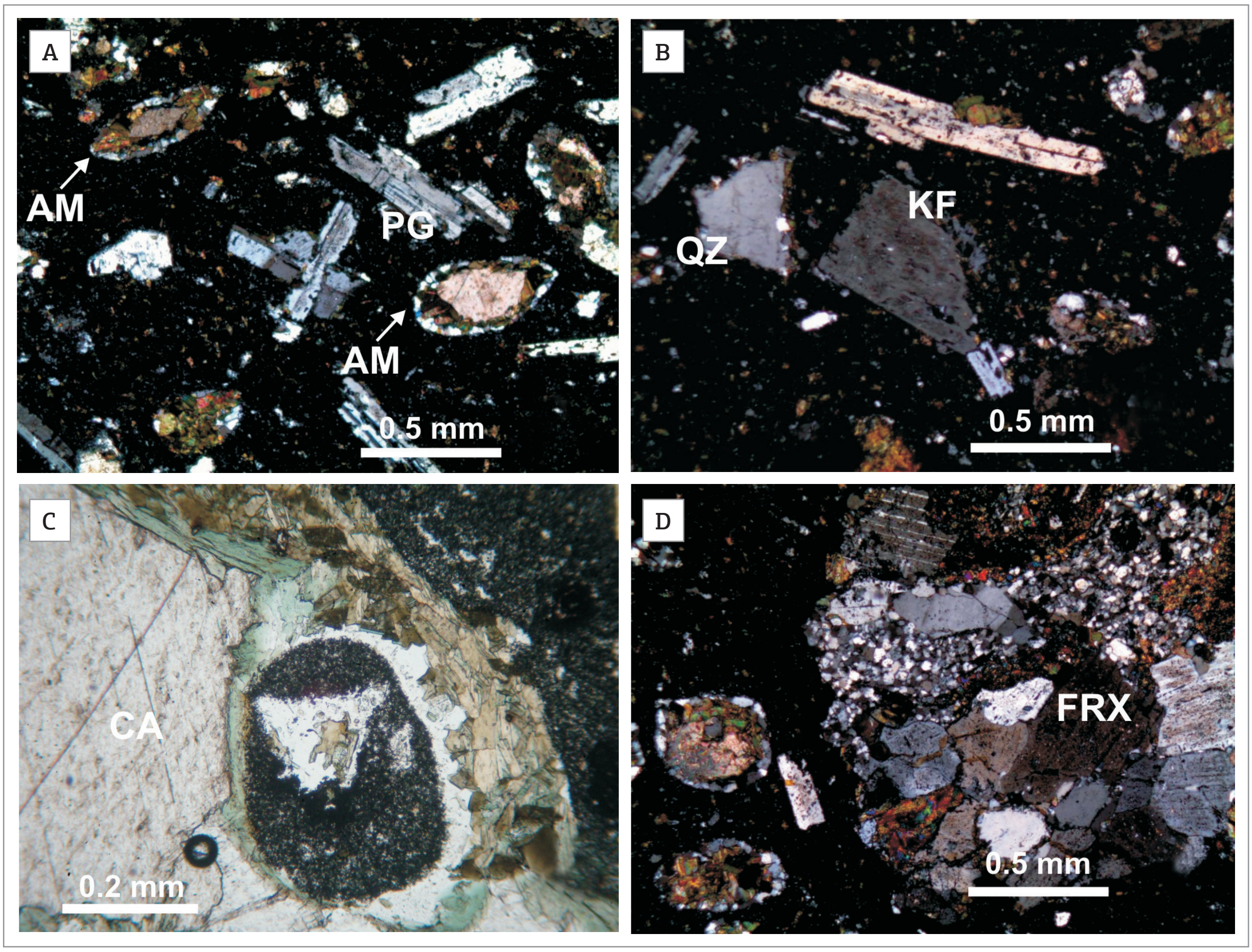

Figure 3. (A) Textural appearance of the rock showing phenocrysts of plagioclase (PG) and the amygdales (AM) filled by quartz + carbonate + phyllosilicates in abundant thin matrix. (B) Detail of tabular phenocrysts of plagioclase, K-feldspar (KF) and quartz (QZ) in thin matrix. (C) Detail of carbonate crystal (CA) bordered by biotite + chlorite, and an amygdale filled by chlorite, carbonate and biotite on center. (D) Granitoid rock fragment (FRX) on thin matrix (all photos with crossed nicols).

Table 1. Chemical analysis of major, minor, and trace elements by ICP-OS, and rare earth elements by ICP-MS (SGS-Geosol Laboratory, Vespasiano-MG). All iron contained as Fe_2O_3

Sample	SiO_2 %	Al_2O_3 %	TiO_2 %	Fe_2O_3 %	MnO %	MgO %	CaO %	Na_2O %	K_2O %	P_2O_5 %	PF %	Total %
Vul-01	52.5	15.6	3.15	8.99	0.16	3.76	6.67	4.46	1.22	1.22	2.38	100.11
Vul-02	64.6	14.4	0.83	7.01	0.12	3.37	1.98	2.87	2.04	0.13	3.07	100.42
Vul-03	50.4	15.0	3.38	8.77	0.15	3.66	8.06	5.07	1.21	1.32	2.82	100.74
Vul-04	50.1	15.6	2.94	8.66	0.17	4.10	5.40	4.98	0.99	1.08	2.46	
Vul-05	53.1	16.3	2.65	9.13	0.16	4.29	5.09	4.59	1.28	0.97	2.37	

Sample	Ba ppm	Sr ppm	Sc ppm	Co ppm	Cu ppm	Zr ppm	Y ppm	V ppm	Cr ppm	Ni ppm	Pb ppm	Th ppm	U ppm
Vul-01	287	398	34	19	7	290	71	173	32	32	< 8	7.2	4.66
Vul-02	1459	163	13	15	9	62	22	85	133	62	14	15.9	3.82
Vul-03	264	451	11	15	7	253	76	188	22	24	11	4.4	3.41
Vul-04	273	267	nd	24	51	340	58	170	nd	43	nd	7.8	4.17
Vul-05	401	282	nd	23	27	317	51	145	nd	49	nd	7.5	4.39

Sample	La ppm	Ce ppm	Pr ppm	Nd ppm	Sm ppm	Eu ppm	Gd ppm	Tb ppm	Dy ppm	Ho ppm	Er ppm	Tm ppm	Yb ppm	Lu ppm
Vul-01	74.2	144.6	17.19	70.6	15.5	4.52	13.74	2.03	10.25	2.20	6.14	0.80	6.0	0.77
Vul-02	33.1	57.6	5.96	23.1	4.3	1.08	4.26	0.64	3.23	0.72	2.49	0.28	2.8	0.41
Vul-03	81.4	118.4	15.65	53.5	10.6	5.21	14.35	2.01	11.42	2.17	4.98	0.76	4.8	0.57
Vul-04	54.7	121.0	15.97	68.2	13.5	4.39	13.35	1.97	11.22	2.19	5.83	0.77	4.8	0.80
Vul-05	48.2	102.5	12.83	55.3	11.3	3.95	10.34	1.61	8.53	1.65	4.74	0.63	4.1	0.71

nd: not determined.

Table 2. Fractionation degree of rare earth elements distribution pattern in the studied samples, based on the ratio La/Lu of the values normalized to North American Shale Composite (according to Haskin *et al.* 1968)

	La (ppm)	La (NASC)	LaN	Lu (ppm)	Lu (NASC)	LuN	FD
Vul-01	74.2	32	2.319	0.77	0.48	1.604	1.45
Vul-02	33.0	32	1.031	0.41	0.48	0.854	1.21
Vul-03	81.4	32	2.544	0.57	0.48	1.188	2.14
Vul-04	54.70	32	1.709	0.80	0.48	1.667	1.03
Vul-05	48.02	32	1.501	0.71	0.48	1.479	1.01

NASC: North American Shale Composite; FD: fractionation degree.

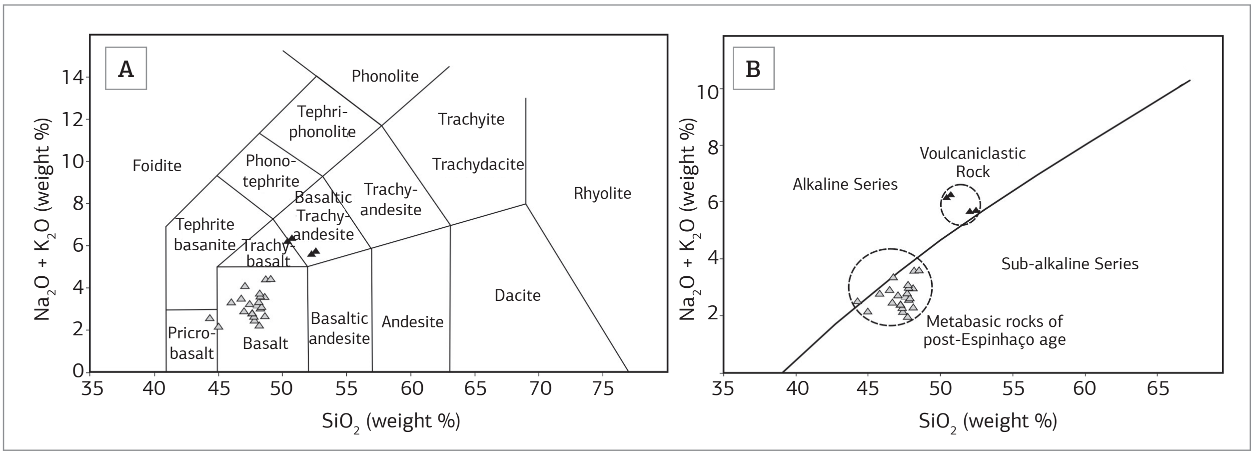

Figure 4. Chemical classification diagrams of the volcaniclastic rock from Gouveia. (A) TAS (total alkalis versus silica) diagram, according to Le Bas *et al.* (1986). (B) Total alkalis versus silica diagram, according to Irvine & Baragar (1971).

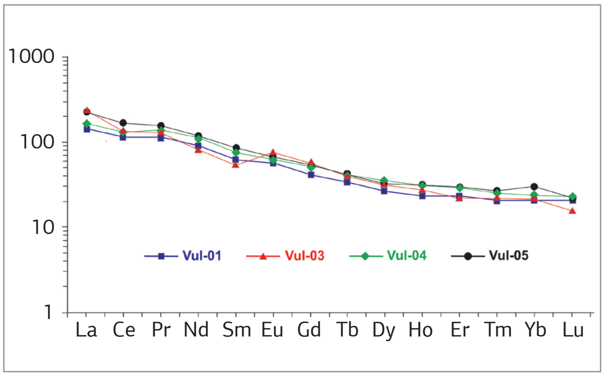

Figure 5. Spidergram with the distribution pattern of rare earth elements normalized to chondrite in the volcaniclastic rock from Gouveia (according to Haskin *et al.* 1968).

U/Pb Geochronology

Zircons were separated from the rock sample following the standard methods used at the University of Ouro Preto laboratory. U-Pb dating was carried out at the Geochronology Research Center of the São Paulo University. The zircon grains are round and slightly rounded with sizes ranging from 80 e 310 mm, mostly between 100 and 200 mm; a few grains show euhedral shape. Grains were mounted in an epoxy disk and polished to expose their centers. Internal structures of zircon grains were revealed by cathodoluminescence (CL-image) using a Quanta 250 FEG electron microscope and most of them show oscillatory zoning igneous pattern (Fig. 6). U-Pb analyses by LA-MC-ICP-MS were carried out on a Neptune coupled to an excimer ArF laser ablation system. Corrections were done for background, instrumental mass bias drift, and common Pb. The ages were calculated using ISOPLOT 3.0 (Ludwig 2003).

Seventy-three grains were dated and only two showed discordancy greater than 8%. The U-Pb ages range from 1.16 to 3.36 Ga (Tab. 3), but 67% of the ages (51 grains) are in the 1.8 – 2.2 Ga interval, indicating that these ages represent the main source rocks of the volcaniclastic deposit (Fig. 7). Archean sources, mainly in the 2.7 to 2.9 Ga interval, also contribute with detritus (~ 23% of the grains). Six grains (~ 8%) show younger ages ranging from 1.16 to 1.23 Ga, and the youngest grain has an $^{238}U/^{206}Pb$ age of 1.163 ± 12 Ma (100% concordant). The CL images of the younger zircons (Fig. 6) reveal that their shapes vary from euhedral (spot 42.1) to round ones (spot 32.1). In addition, they do not show metamorphic overgrowths, which coupled with the oscillatory zoning pattern, support an igneous origin of the grains. These results allow us to set the maximum depositional age of the volcaniclastic rock at 1.16 Ga.

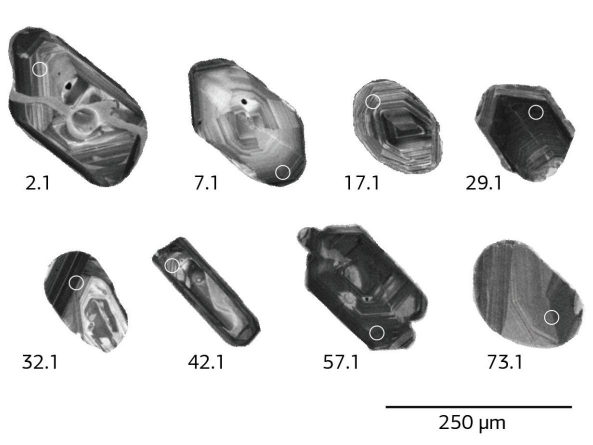

Figure 6. CL images showing internal structures of some zircons from sample Vul-1A. Circles indicate the spot position and numbers represent the dated grain which ages are presented in Tab. 3.

DISCUSSIONS

The U-Pb ages obtained on zircons from sample Vul-1A show a large range and are very critical to better understand the evolution of the Espinhaço Supergroup (Fig. 7).

The Basal Complex in the Gouveia region (Brito Neves *et al.* 1979, Machado *et al.* 1989) could be the source of the late Archean grains (mainly between 2.7 to 2.9 Ga). A 3.3 Ga single age (zircon grain 73.1 in Tab. 3) probably refers to some inherited zircon of an oldest rock, common in Proterozoic metasediments of the Espinhaço Range (Sano *et al.* 2002, Martins *et al.* 2008, Chemale Jr. *et al.* 2011, 2012).

The presence of Paleoproterozoic zircons (1.8 to 2.2 Ga) is also important for the regional geologic framework interpretation. The presence of schists, volcanic and BIF clasts (Fig. 2B) in the volcaniclastic rock, suggest that such zircons could be derived from them. In addition, Chaves *et al.* (2012) correlated the iron formations of Pedro Pereira Formation (redefined), which crops out nearby, with those occurring in the Serra da Serpentina, in the Conceição do Mato Dentro region (Paleoproterozoic, according to Dossin *et al.* 1987), based on the REEs geochemical similarities of both units. Until then, the Pedro Pereira Formation was considered part of an Archean volcano-sedimentary sequence (Fogaça *et al.* 1984).

The ages determined for the younger ages range in a very narrow time interval (1.21 and 1.25 Ga) and suggest that they were crystallized *in situ*. Such ages are typical of the event worldwide known as Grenvillian (Gower & Krogh 2002, Cordani *et al.* 2010) and, if represents the age of the rock crystallization, constitute the first record of such magmatism in Southern Espinhaço. Recently detrital zircons with similar age were reported in the matrix of the diamond-bearing conglomerates of the Sopa-Brumadinho Formation, in Diamantina region (Chemale Jr. *et al.* 2011, 2012; Santos *et al.* 2013) and the Grão Mogol Formation, in the town with the same name (Chaves *et al.* 2013).

The Grenville Tectonic Province of Canada is considered as a record of the Supercontinent Rodinia agglutination process, and took place in the mid to late Mesoproterozoic (e.g. Gower & Krogh 2002, Rivers 1997). The correlation of this event with the records of the Espinhaço Supergroup, however, is difficult since there are no data of orogenic inversion on the Espinhaço basin in this time interval. Nevertheless, there are records of compressional nature events within the São Francisco Craton whose origins are poorly understood, as described by Cordani *et al.* (2010). Such events had been interpreted by such authors as reflections of collisional processes in neighboring cratons, as in the Congo Craton, in Eastern Africa. However, this hypothesis is not shared by Zalan & Silva (2007) who, based on the interpretation of seismic sections in the São Francisco basin, suggest a total inversion of Statherian rifts between 1.3 and 1.0 Ga.

CONCLUDING REMARKS

Detrital zircons with Grenvillian ages in the conglomerates of the Sopa-Brumadinho Formation, in the Diamantina region, rejuvenates the sedimentation age of this formation and the entire upper stratigraphic column of the Espinhaço Supergroup. If these ages are confirmed, a new scenario for the geotectonic evolution of the Espinhaço Supergroup should be revealed. The Grenville period has been considered in the peripheral zone to the São Francisco-Congo craton as a "not orogenic time". However, the existence of compressive Mesoproterozoic events in Southern Espinhaço has always been the subject of many discussions, some arguing (e.g., Brito-Neves *et al.* 1995, Almeida-Abreu & Renger 2002), others not admitting the event (e.g., Uhlein *et al.* 1998, Alkmim *et al.* 2006), although those who defend the orogenic event had in mind a classic orogen, called "Espinhaço" or "Uruaçuano".

Our geochronological data suggest that there are one or more magmatic events during the Grenvillian period. Thus, a great part of the Espinhaço basin geological history should be revised in order to understand its stages of extension and subsequent sedimentation. In addition, orogenic processes and/or compressional tectonics may have not

Table 3. U-Pb isotopic data on zircons of sample Vul-1A, from the Gouveia area, Southern Espinhaço Range

						Radiogenic Ratios							Ages (Ma)						
Grain. spot	U (ppm)	Th (ppm)	Th/U	$^{206}Pb^*$ (ppm)	Pbc %	$^{206}Pb/^{238}U$	±	$^{207}Pb/^{235}U$	±	$^{207}Pb/^{206}Pb$	±	r	$^{206}Pb/^{238}U$	±	$^{207}Pb/^{235}U$	±	$^{207}Pb/^{206}Pb$	±	% Disc
1.1	233	94	0.40	115	0.24	0.4040	0.0021	7.3541	0.0747	0.1318	0.0008	0.52	2187	10	2155	9	2119	10	- 3
2.1	213	102	0.48	54	1.39	0.2110	0.0011	2.3588	0.0243	0.0815	0.0006	0.49	1234	6	1230	7	1238	14	0
3.1	223	81	0.36	150	0.02	0.5326	0.0040	14.0467	0.1776	0.1900	0.0012	0.59	2752	17	2753	12	2746	11	0
4.1	206	141	0.69	102	< 0.001	0.3813	0.0020	6.7822	0.0692	0.1284	0.0008	0.51	2082	9	2083	9	2073	10	0
5.1	437	272	0.62	81	5.97	0.1357	0.0045	1.6417	0.0384	0.0848	0.0009	0.99	820	26	986	15	1316	20	38
6.1	86	107	1.25	48	< 0.001	0.3791	0.0019	6.6757	0.0669	0.1275	0.0008	0.51	2072	9	2069	9	2062	11	0
7.1	48	25	0.52	24	0.39	0.3963	0.0022	7.1280	0.0785	0.1292	0.0010	0.50	2152	10	2128	10	2084	14	- 3
8.1	72	31	0.43	34	0.48	0.3799	0.0020	6.7973	0.0714	0.1281	0.0008	0.50	2076	9	2085	9	2070	11	0
9.1	109	51	0.47	47	< 0.001	0.3477	0.0031	5.6963	0.0453	0.1192	0.0007	0.90	1924	15	1931	7	1944	11	1
10.1	70	37	0.53	39	< 0.001	0.4077	0.0043	7.7459	0.0813	0.1386	0.0009	0.90	2204	20	2202	9	2206	11	0
11.1	36	33	0.93	17	< 0.001	0.3557	0.0036	5.9365	0.0516	0.1202	0.0009	0.99	1962	17	1967	8	1959	13	0
12.1	202	97	0.48	90	< 0.001	0.3572	0.0032	6.0033	0.0475	0.1216	0.0007	0.99	1969	15	1976	7	1979	10	0
13.1	76	77	1.01	36	0.39	0.3404	0.0032	5.7297	0.0518	0.1221	0.0009	0.99	1888	16	1936	8	1987	12	5
14.1	79	87	1.09	40	< 0.001	0.3574	0.0032	5.9978	0.0466	0.1215	0.0007	0.99	1970	15	1976	7	1978	10	0
15.1	61	34	0.55	30	1.48	0.3999	0.0040	7.4260	0.0737	0.1349	0.0011	0.99	2168	19	2164	9	2159	14	0
16.1	59	37	0.62	41	< 0.001	0.5397	0.0050	14.5624	0.1181	0.1943	0.0012	0.99	2782	21	2787	8	2784	10	0
17.1	121	49	0.40	58	0.24	0.3996	0.0033	7.4736	0.1099	0.1361	0.0021	0.55	2167	15	2170	13	2174	26	0
18.1	132	101	0.77	95	< 0.001	0.5398	0.0044	14.5440	0.2112	0.1956	0.0029	0.56	2783	18	2786	14	2795	25	0
19.1	98	44	0.45	70	< 0.001	0.5465	0.0044	14.9722	0.2150	0.1988	0.0030	0.55	2811	18	2813	14	2822	24	0
20.1	90	63	0.70	38	< 0.001	0.3246	0.0026	4.9505	0.0721	0.1107	0.0017	0.55	1812	13	1811	12	1814	27	0
21.1	185	149	0.80	98	0.20	0.3955	0.0031	7.2323	0.1035	0.1317	0.0020	0.55	2148	14	2140	13	2118	25	- 1
22.1	140	98	0.70	62	< 0.001	0.3389	0.0027	5.4338	0.0781	0.1154	0.0017	0.56	1881	13	1890	12	1888	26	0
23.1	85	87	1.03	45	0.15	0.3855	0.0040	7.0019	0.1057	0.1324	0.0020	0.68	2102	18	2112	13	2127	26	1
24.1	59	46	0.77	42	< 0.001	0.5188	0.0044	13.6698	0.2048	0.1885	0.0029	0.56	2694	18	2727	14	2732	25	1
25.1	99	58	0.58	46	< 0.001	0.3619	0.0035	6.1541	0.0705	0.1230	0.0011	0.85	1991	17	1998	10	2000	16	0
26.1	47	17	0.36	23	< 0.001	0.4015	0.0039	7.5023	0.0856	0.1370	0.0013	0.86	2176	18	2173	10	2185	16	0
27.1	97	75	0.78	42	< 0.001	0.3269	0.0032	5.1339	0.0588	0.1130	0.0010	0.86	1823	16	1842	10	1850	16	1
28.1	150	91	0.60	81	< 0.001	0.4114	0.0042	7.9270	0.0942	0.1405	0.0013	0.86	2221	19	2223	11	2229	16	0
29.1	245	133	0.54	159	< 0.001	0.4897	0.0049	13.4057	0.1594	0.1967	0.0017	0.85	2569	21	2709	11	2804	15	8
30.1	103	42	0.41	50	< 0.001	0.3956	0.0039	7.3812	0.0855	0.1356	0.0012	0.85	2149	18	2159	10	2168	16	1
31.1	87	110	1.27	73	< 0.001	0.5485	0.0053	15.0419	0.1715	0.1999	0.0018	0.85	2819	22	2818	11	2831	15	0
32.1	250	106	0.42	63	< 0.001	0.2072	0.0021	2.3619	0.0280	0.0818	0.0007	0.84	1214	11	1231	8	1246	18	3
33.1	263	13	0.05	97	1.56	0.3356	0.0035	5.6635	0.0687	0.1222	0.0011	0.86	1866	17	1926	10	1988	16	6
34.1	225	167	0.74	175	< 0.001	0.5653	0.0059	15.9555	0.1919	0.2032	0.0018	0.87	2889	24	2874	11	2858	15	- 1
35.1	179	96	0.54	88	0.49	0.3914	0.0038	7.2257	0.0840	0.1328	0.0012	0.83	2129	18	2140	10	2132	15	0
36.1	56	49	0.88	30	< 0.001	0.3941	0.0039	7.2844	0.0855	0.1329	0.0013	0.85	2142	18	2147	10	2133	16	0
37.1	570	2581	4.53	442	0.21	0.3397	0.0036	5.4555	0.1415	0.1155	0.0029	0.41	1885	17	1894	22	1889	43	0
38.1	101	40	0.40	49	0.28	0.3937	0.0044	7.6214	0.0779	0.1395	0.0013	0.90	2140	20	2187	9	2216	17	3
39.1	129	57	0.44	58	< 0.001	0.3620	0.0031	6.2113	0.0358	0.1233	0.0009	0.90	1991	15	2006	5	2004	13	1
40.1	194	53	0.27	97	5.50	0.3743	0.0040	6.6831	0.0555	0.1267	0.0010	0.99	2050	19	2070	7	2051	14	0
40.2	140	25	0.18	57	< 0.001	0.3466	0.0030	5.9273	0.0353	0.1229	0.0010	0.99	1918	14	1965	5	1998	14	4
41.1	46	37	0.80	12	< 0.001	0.1978	0.0022	2.1168	0.0270	0.0786	0.0011	0.87	1163	12	1154	9	1165	29	0
41.2	359	382	1.06	103	2.08	0.2059	0.0018	2.2904	0.0169	0.0805	0.0007	0.99	1207	10	1209	5	1212	18	0
42.1	188	134	0.71	46	2.21	0.1994	0.0023	2.2451	0.0227	0.0815	0.0008	0.99	1172	12	1195	7	1239	18	5
43.1	170	125	0.74	86	< 0.001	0.3769	0.0032	6.6366	0.0375	0.1269	0.0010	0.99	2062	15	2064	5	2053	13	0
44.1	123	45	0.37	88	< 0.001	0.5600	0.0047	16.5497	0.0892	0.2136	0.0016	0.99	2867	20	2909	5	2939	12	2
45.1	267	234	0.88	118	1.45	0.3148	0.0039	5.0402	0.0644	0.1138	0.0010	0.96	1764	19	1826	11	1863	15	5
46.1	74	18	0.24	35	< 0.001	0.3956	0.0037	7.3070	0.0475	0.1319	0.0010	0.99	2149	17	2150	6	2120	13	- 1
47.1	180	259	1.44	110	0.05	0.4154	0.0051	8.2794	0.1197	0.1420	0.0013	0.85	2240	23	2262	13	2247	16	0
48.1	76	46	0.60	38	< 0.001	0.3877	0.0034	7.2355	0.0420	0.1336	0.0010	0.99	2112	16	2141	5	2143	13	1
49.1	139	82	0.59	71	< 0.001	0.3990	0.0025	7.5501	0.0526	0.1361	0.0007	0.91	2164	12	2179	6	2175	9	0
50.1	68	67	0.99	49	0.31	0.5251	0.0035	13.3981	0.0965	0.1833	0.0010	0.93	2721	15	2708	7	2685	9	- 1
51.1	258	142	0.55	154	0.04	0.4588	0.0029	10.0878	0.0694	0.1594	0.0008	0.92	2434	13	2443	6	2446	8	0
52.1	95	82	0.86	50	0.56	0.4013	0.0032	7.2852	0.0664	0.1322	0.0008	0.87	2175	15	2147	8	2124	10	- 2
53.1	89	80	0.89	42	< 0.001	0.3454	0.0024	5.6139	0.0437	0.1154	0.0006	0.87	1913	11	1918	7	1887	9	- 1
54.1	100	75	0.75	76	< 0.001	0.5576	0.0057	15.4987	0.1953	0.2033	0.0015	0.80	2857	23	2846	12	2859	12	0
55.1	145	61	0.42	62	< 0.001	0.3508	0.0023	5.8639	0.0425	0.1203	0.0006	0.92	1939	11	1956	6	1960	9	1
56.1	336	369	1.10	155	1.28	0.2954	0.0063	6.4214	0.2124	0.1629	0.0014	0.64	1669	31	2035	29	2483	15	33
57.1	329	171	0.52	82	0.20	0.2023	0.0014	2.2707	0.0168	0.0805	0.0004	0.93	1188	7	1203	5	1214	10	2
58.1	37	20	0.52	25	< 0.001	0.5048	0.0034	12.8248	0.0963	0.1826	0.0010	0.90	2634	15	2667	7	2678	9	2
59.1	177	182	1.03	85	< 0.001	0.3417	0.0023	5.5015	0.0416	0.1158	0.0006	0.89	1895	11	1901	6	1893	9	0
60.1	304	246	0.81	219	< 0.001	0.5218	0.0034	13.4119	0.0936	0.1849	0.0009	0.92	2707	14	2709	7	2700	8	0
61.1	129	84	0.65	61	< 0.001	0.3652	0.0072	5.9270	0.2459	0.1239	0.0009	0.48	2007	34	1965	35	2012	13	0
62.1	72	28	0.38	34	0.19	0.3965	0.0070	7.2989	0.2242	0.1329	0.0021	0.57	2153	32	2149	27	2134	27	- 1
63.1	161	112	0.69	74	0.04	0.3689	0.0065	6.2966	0.1926	0.1218	0.0019	0.57	2024	30	2018	26	1982	27	- 2
64.1	52	95	1.83	30	< 0.001	0.3672	0.0066	6.2473	0.1938	0.1218	0.0019	0.58	2016	31	2011	27	1982	27	- 2
65.1	85	35	0.41	41	< 0.001	0.4055	0.0071	7.7006	0.2361	0.1370	0.0021	0.57	2194	33	2197	27	2186	27	0
66.1	185	154	0.83	99	0.25	0.4124	0.0072	7.7425	0.2373	0.1344	0.0021	0.57	2226	33	2202	27	2153	26	- 3
67.1	163	70	0.43	70	0.07	0.3649	0.0064	6.1819	0.1895	0.1214	0.0019	0.57	2005	30	2002	26	1977	27	- 1
68.1	103	72	0.69	54	0.10	0.4198	0.0074	7.8245	0.2390	0.1337	0.0021	0.58	2260	33	2211	27	2143	26	- 5
69.1	124	94	0.76	93	< 0.001	0.5682	0.0099	16.2962	0.4973	0.2072	0.0032	0.57	2900	41	2894	29	2890	25	0
69.2	80	49	0.61	55	< 0.001	0.5378	0.0094	14.1912	0.4335	0.1893	0.0029	0.57	2774	39	2763	29	2740	26	- 1
70.1	54	61	1.14	29	0.21	0.3917	0.0070	7.1025	0.2189	0.1294	0.0021	0.58	2131	32	2124	27	2087	28	- 2
71.1	159	96	0.61	78	0.09	0.3974	0.0070	7.3228	0.2242	0.1323	0.0020	0.57	2157	32	2152	27	2126	26	- 1
72.1	158	48	0.31	74	< 0.001	0.4030	0.0073	7.3700	0.2282	0.1318	0.0020	0.58	2183	33	2157	27	2119	26	- 3
73.1	129	66	0.51	117	0.07	0.6878	0.0120	26.7727	0.8187	0.2800	0.0043	0.57	3374	46	3375	29	3358	24	0

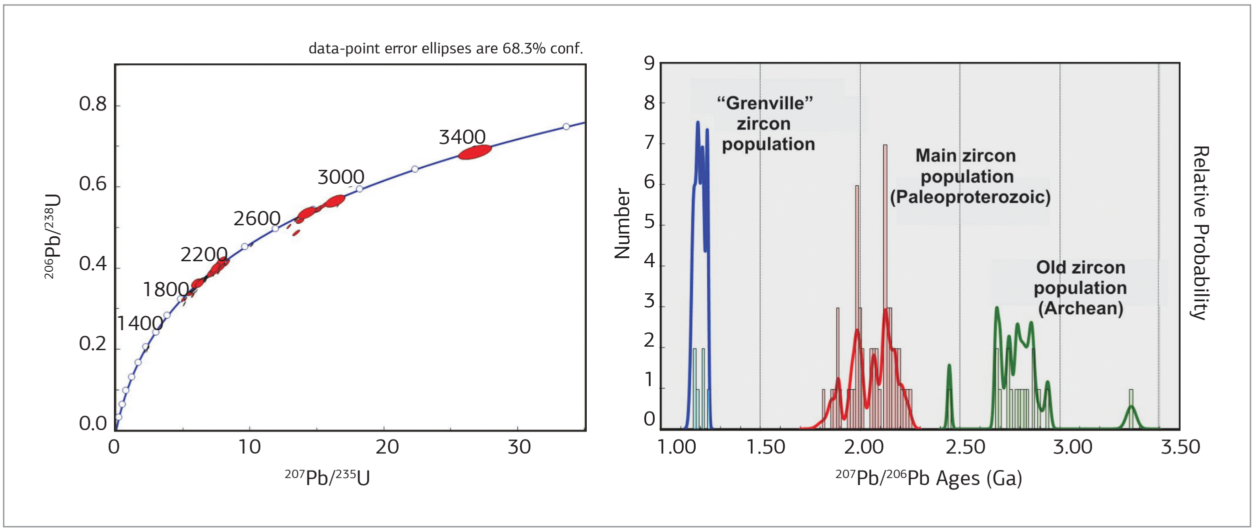

Figure 7. U-Pb concordia diagram (A) and age histogram (B) of zircons from sample Vul-1A.

affected these units during the Mesoproterozoic. Instead, the possible explosive volcanism characteristics evidenced by the deposit studied in Gouveia, with chemistry of basic-alkaline tendency, are consistent with a new phase of basin extension and rifting in the 1.25 to 1.10 Ga interval. This is confirmed by younger zircon dated in this study, as well as those reported by Chemale Jr. *et al.* (2011, 2012) and Santos *et al.* (2013), whose magmatisms are certainly associated with the evolution of sedimentation processes that affect the Sopa-Brumadinho Formation in Southern Espinhaço.

ACKNOWLEDGMENTS

The first author thanks FAPEMIG for the research grant (Process CRA-APQ-01255-09), which funded the geochronological study. MLSCC and MB thank CNPq for the research fellowship. The descriptions and petrographic microphotographs were performed by the geologists Andrezza Azzi and Ludmila Pereira, which the authors also thank. We also thank the editor, Prof. Cordani, and two reviewers for the thoughtful and detailed reviews, which helped to improve the manuscript.

REFERENCES

Alkmim F.F., Marshak S., Pedrosa Soares A.C., Peres G.G., Cruz S.C.P. & Washington A. 2006. Kinematic evolution of the Araçuaí-West Congo orogen in Brazil and Africa: Nutcracker tectonics during Neoproterozoic assembly of Gondwana. *Precambrian Research*, **149**:43-64.

Alkmim F.F. & Martins-Neto M.A. 2012. Proterozoic first-order sedimentary sequences of the São Francisco craton, eastern Brazil. *Marine and Petroleum Geology*, **33**:127-139.

Almeida F.F.M. 1977. O Cráton do São Francisco. *Revista Brasileira de Geociências*, **7**:349-364.

Almeida Abreu P.A. & Renger F.E. 2002. Serra do Espinhaço Meridional, um orógeno do Mesoproterozóico. *Revista Brasileira de Geociências*, **32**:1-14.

Babinski M., Pedrosa-Soares A.C., Trindade R.I.F., Martins M., Noce C.M. & Liu D. 2012. Neoproterozoic glacial deposits from the Araçuaí orogen, Brazil: age, provenance, and correlations with the São Francisco cráton and West Congo belt. *Gondwana Research*, **21**:451-465.

Brito-Neves B.B., Kawashita K., Cordani U.G. & Delhal J. 1979. A evolução geocronológica da Serra do Espinhaço; dados novos e integração. *Revista Brasileira de Geociências*, **9**:71-85.

Brito-Neves B.B., Sá J.M., Nílson A.A. & Botelho N.F. 1995. A tafrogênese Estateriana nos blocos paleoproterozóicos da América do Sul e processos subseqüentes. *Geonomos*, **3**:1-21.

Carvalho A.S. 1982. *Geologia e gênese das mineralizações de quartzo no Espinhaço Meridional, Minas Gerais, Brasil*. Dissertação de Mestrado, Universidade de Brasília, Brasília, 94 p.

Chaves M.L.S.C., Silva M.C.R., Chaves A.O. & Dussin T.M. 2012. Formações ferríferas bandadas no Grupo Costa Sena (Gouveia-MG, Brasil). *In:* Lopes F.C. *et al.* (coords.) *Para Conhecer a Terra. Memórias e Notícias no Espaço Lusófono*. Coimbra, Univ. de Coimbra Press, v. 1, c. 26, p.251-260.

Chaves M.L.S.C., Babinski M., Silva M.C.R. & Scholz R. 2013. Idades U-Pb em zircão do conglomerado diamantífero de Grão Mogol (Supergrupo Espinhaço): implicações para a origem dos diamantes da Serra do Espinhaço em Minas Gerais. *Brazilian Journal of Geology*, **43**:139-151.

Chemale Jr. F., Dussin I.A., Alkmim F.F., Martins M.S., Queiroga G., Armstrong, R. & Santos, M.N. 2012. Unravelling a Proterozoic basin history through detrital zircon geochronology: the case of the Espinhaço Supergroup, Minas Gerais, Brazil. *Gondwana Research*, **22**:200-206.

Cordani U.G., Fraga L.M., Reis N. & Tassinari C.C.G., Brito-Neves B.B. 2010. On the origin and tectonic significance of the intra-plate events of Grenvillian-type age in South America: a discussion. *Journal of South American Earth Sciences*, **29**:143-159.

Corrêa-Gomes L.C. & Oliveira E.P. 2000. Radiating 1.0 Ga mafic dyke swarms of eastern Brazil and western Africa: evidence of post-assembly extension in the Rodinia supercontinent? *Gondwana Research*, **3**:325-332.

Cox K.G., Bell J.D. & Pankhurst R.J. 1979. *The Interpretation of Igneous Rocks*. New York, George Allen & Unwin, 293 p.

Cruz S.C., Alkmim F.F. & Lagoeiro L.E. 2005. Zonas de cisalhamento do núcleo do Anticlinório de Gouveia, Cordilheira do Espinhaço, MG: geometria, cinemática e processos deformacionais. *Revista Brasileira de Geociências*, **35**:441-452.

Danderfer A., De Waele B., Pedreira A. & Nalini H.A. 2009. New geochronological constraints on the geological evolution of Espinhaço basin within the São Francisco craton – Brazil. *Precambrian Research*, **95**:9-39

Dossin I.A., Dossin T.M. & Chaves M.L.S.C. 1990. Compartimentação estratigráfica do Supergrupo Espinhaço em Minas Gerais – os grupos Diamantina e Conselheiro Mata. *Revista Brasileira de Geociências*, **20**:178-186.

Dossin T.M., Dossin I.A. & Dardenne M.A. 1987. Geoquímica dos elementos terras raras das formações ferríferas da Serra da Serpentina, Conceição do Mato Dentro, MG. *Geochimica Brasiliensis*, 1:151-160.

Dussin T.M. 1994. *Associations plutono-volcaniques de l'Espinhaço Méridional: un exemple d'évolution de la croûte protérozoïque.*Tese de Doutorado, Université d'Orléans, Orléans, 177 p.

Fogaça A.C.C., Almeida-Abreu P.A., Schorcher H.D. 1984. Estratigrafia da sequência supracrustal arqueana na porção mediana-central da Serra do Espinhaço, Minas Gerais. *In:* SBG, Congresso Brasileiro de Geologia, **33**, Rio de Janeiro, *Anais*, v. 8, p. 2654-2667.

Gower C.F. & Krogh T.E. 2001. A U-Pb geochronological review of the Proterozoic history of the eastern Grenville Province. *Canadian Journal of Earth Sciences*, **39**:795-829.

Haskin L.A., Haskin M.A., Frey F.A. & Wildeman T.R. 1968. Relative and absolute terrestrial abundances of the rare earths. *In:* Ahrens L.H. (ed.) *Origin and Distribution of the Elements*. Pergamon, Oxford, p. 889-912.

Hoffmann C. 1980. Neugliederung und geologische Geschichte der "Präminas-Gesteine" in der südlichen Serra do Espinhaço, Minas Gerais, Brasilien. *Münstersche Forschungen zur Geologie und Paläontologie*, **51**:183-197.

Hoffmann C. 1983. The Archean peraluminous Gouveia Granite, its structure, geochemistry, and phase petrology (Serra do Espinhaço, Minas Gerais, Brazil). *Neues Jahrbuch Mineral. Abh.*, **146**:151-169.

Hoppe A., Hörmann P.K. & Eulert M.H. 1983. Padrões de terras raras de rochas básicas proterozóicas da Serra do Espinhaço, MG. *In:* SBG, Simpósio de Geologia de Minas Gerais, 2, Belo Horizonte, *Anais*, p.143-147.

Irvine T.N. & Baragar W.R.A. 1971. A guide to the chemical classification of the common volcanic rocks. *Canadian Journal of Earth Sciences*, **8**:523-548.

Le Bas M.J., LeMaitre R.W., Streckeisen A. & Zanettin B. 1986. A chemical classification of volcanic rocks based on the total alkali-silica diagram: *Journal of Petrology*, **27**:745-750.

Ludwig K.R. 2003. *User's manual for Isoplot/Ex Version 3.0. A geochronological toolkit for Microsoft Excel*. Berkeley Geochronological Center, Special Publication 1a, Berkeley, USA, 55p.

Machado N., Schrank A., Abreu F.R., Knauer L.G. & Almeida-Abreu P.A. 1989. Resultados preliminares da geocronologia U/Pb na Serra do Espinhaço Meridional. *In:* SBG, Simpósio de Geologia de Minas Gerais, 5, Belo Horizonte, *Anais*, p.171-174.

Pedrosa-Soares A.C., Babinski M., Noce C., Martins M., Queiroga G. & Vilela F. 2011. The Neoproterozoic Macaúbas Group, Araçuaí orogen, SE Brazil. *In:* Arnaud E., Halverson G.P., Shields-Zhou G. (eds), *The Geological Record of Neoproterozoic Glaciations*. Geological Society, London, Memoirs 36, p. 523-534.

Rivers T. 1997. Lithotectonic elements of the Grenville Province. Review and tectonic implications. *Precambrian Research*, **86**:117-154.

Sano I., Yokoshi R., Chaves M.L.S.C. & Ozima M. 2002. Ion microprobe Pb-Pb dating of carbonado, polycristalline diamond. *Precambrian Research*, **11**:155-168.

Santos M.N., Chemale Jr. F., Dussin I.A., Martins M., Assis T.A.R. & Jelinek A.R. 2013. Sedimentological and paleoenvironmental constraints of the Statherian and Stenian Espinhaço rift system, Brazil. *Sedimentary Geology*, **290**:47-59.

Uhlein A., Trompette R. & Silva M.E. 1998. Proterozoic rifting and closure, SE border of the São Francisco Craton, Brazil. *Journal of South American Earth Sciences*, **11**:191-203

Zalán P.V. & Silva P.C.R. 2007. Bacia do São Francisco. *Boletim de Geociências da Petrobrás*, **15**:561-571.