Geologia USP Série Científica

DOI: 10.11606/issn.2316-9095.v18-125793

Revista do Instituto de Geociências - USP

Geol. USP, Sér. cient., São Paulo, v. 18, n. 2, p. 45-56, Junho 2018

U-Pb dating, Lu-Hf isotope systematics and chemistry of zircon from the Morro do Polvilho meta-trachydacite: constraints on sources of magmatism and on the depositional age of the São Roque Group

Datação U-Pb, sistemática isotópica Lu-Hf e química de zircão do metatraquidacito do Morro do Polvilho: contribuição para fonte do magmatismo e para a idade deposicional do Grupo São Roque

Renato Henrique-Pinto[1], Valdecir de Assis Janasi[2], Ginaldo Ademar da Cruz Campanha[2]

[1]Département de Géologie et de Génie Géologique, Faculté des Sciences et de Génie, Université Laval, 1065 Avenue de la Médecine, Québec, QC G1V 0A6, CA (renato.henrique-pinto.1@ulaval.ca)

[2]Instituto de Geociências, Universidade de São Paulo, São Paulo, SP, BR (vajanasi@usp.br; ginaldo@usp.br)

Received on January 26, 2017; accepted on March 14, 2018

Abstract

We present new *in situ* geochronological data of controversial silicic metavolcanic rocks from the lower terrigenous-metavolcanic sequence of the São Roque Group, Ribeira Belt, confirming that they are older than the rocks of higher-metamorphic grade sequences of the Serra do Itaberaba Group. The age of the Polvilho meta-trachydacite was established at 1760 ± 17 Ma, furthermore the results suggest that the bi-modal volcanism of the Boturuna Formation has parent melts from an old (Archean to Paleoproterozoic) continental crust that was melted in a within-plate environment. Trace-element chemistry of zircon, suggests similarities with high-temperature melts (T Zr_{sat} = 900–915ºC) similar to A-type granites (high negative Eu_N/Eu_N* and moderate positive Ce_N/Ce_N*) from continental sources under reducing conditions.

Keywords: Polvilho; Meta-trachydacite; High-temperature melts; Reducing conditions; São Roque Group.

Resumo

Este trabalho apresenta novos dados geocronológicos *in situ* das rochas metavulcânicas ácidas da sequência inferior do Grupo São Roque, São Paulo, Brasil, confirmando que esta é mais jovem que as rochas metamórficas de mais alto grau do Grupo Serra do Itaberaba. A idade do metatraquidacito do Morro do Polvilho foi estabelecida em 1760 ± 17 Ma, com resultados sugerindo que o vulcanismo bimodal da formação Boturuna teve magma parental proveniente de uma crosta continental antiga (Arqueana a Paleoproterozoica), que foi gerado em ambiente intraplaca. A química de elementos-traço em zircão sugere semelhanças com magmas de alta temperatura (T Zr_{sat} = 900-915ºC) como a de granitos do tipo-A (pronunciada Eu_N/Eu_N* negativa e moderada Ce_N/Ce_N* positiva), provenientes de fontes continentais geradas em condições redutoras.

Palavras-chave: Morro do Polvilho; Metatraquidacito; Magma de alta temperatura; Condições redutoras; Grupo São Roque.

INTRODUCTION

Determining the depositional age of the several metasedimentary sequences that extend for large portions of the Mantiqueira Province is fundamental to understand its evolution, but it has been, until recently, a difficult task. Dating by the U-Pb technique of coeval and/or intrusive metavolcanic rocks and of detrital zircons from clastic sequences resulted in great advances in the precise definition of depositional ages, or at least in constraining them to narrow time intervals (e.g., Campanha et al., 2008, 2015, 2016; Siga Jr. et al., 2011).

As with most other sequences in the Ribeira Belt, the age of the São Roque Group has been subject of continued debate. A depositional age of 1395 ± 10 Ma was determined for the Serra do Itaberaba Group based on U-Pb dating of meta-andesitic rocks from its basal portions (Juliani et al., 2000), and was distinguished from the São Roque Group, that was then considered as a post-1.4 Ga sequence, possibly deposited during the Neoproterozoic. U-Pb dating of monazite in a metabasite from the Pirapora do Bom Jesus region yielded an age of 628 ± 9 Ma (Hackspacher et al., 2000) and reinforced this conception. However, a U-Pb TIMS zircon dating of silicic metavolcanic rocks from the Morro do Polvilho region indicated a 1790 ± 14 Ma age, based on two slightly discordant zircon fractions (van Schums et al., 1986).

The magmatic character of these metavolcanic rocks was questioned by Juliani et al. (1997), who interpreted them as metarkoses; consequently, the age obtained by van Schmus et al. (1986) was considered as the age of the main source area. However, field geology and petrography of the Polvilho meta-trachydacite confirmed its metavolcanic character and its whole-rock chemistry indicated a within-plate composition, typical of rift-related sequences (Henrique-Pinto and Janasi, 2010). Moreover, detrital zircons of typical metarenites associated with the São Roque Group show no zircons younger than 1.75 Ga, which is consistent with an older depositional age (Henrique-Pinto et al., 2015b).

We selected one meta-trachydacite sample (MD-06) collected in the Morro do Polvilho region (attributed to the basal Boturuna Formation of the São Roque Group) to perform a new geochronological study, using *in situ* zircon dating by LA-MC-ICPMS, which is capable of circumventing any problems with the ID-TIMS method, since it may provide more concordant results avoiding the presence of inherited core-crystals. This was preceded by a morphological study of the crystals using cathodoluminescence (CL), followed by chemical and Hf isotope determinations in the same crystals, with the objective to characterize the source and magmatic affinities of these silicic volcanics.

GEOLOGICAL SETTING

The Apiaí-São Roque Domain (Campos Neto, 2000) is a tectonic block that includes meta-volcano-sedimentary sequences metamorphosed to low-to-medium-grade conditions, located between high-grade metamorphic rocks of the Socorro-Guaxupé Nappe to the north (interpreted by many authors as related to the evolution of the southern branch of the Brasília Fold Belt), and the Embu Domain to the south (related to the Ribeira Fold Belt).

Within the São Roque Domain, at least two mains metasupracrustal sequences were recognized, the São Roque and Serra do Itaberaba groups. The Serra do Itaberaba Group corresponds to a high-grade volcano-sedimentary sequence composed mainly of basic to intermediate tuffs, volcanic rocks, BIF and detrital sediments (Juliani et al., 2000). The São Roque Group has been considered as younger than the Serra do Itaberaba Group, based on its lower metamorphic grade and the presence, in metaconglomerates, of clasts of metamorphic rocks attributed to the latter (Juliani et al., 2000).

In contrast, the São Roque Group is characterized by a passive continental margin sequence (Henrique-Pinto et al., 2015a) with a two main-fold subdivision. The basal units are characterized by metarkoses interlayered with polymictic metaconglomerates, meta-quartzarenites and small bodies of metavolcanic rocks defined as Boturuna Formation (Hasui et al., 1976), and an upper sequence of meta-mudstones interbedded with metawackes, which may correspond to rhythmic turbidity deposits (Piragibu Fm; e.g., Juliani and Beljavskis, 1995, and references therein) (Figure 1). Later works distinguished the Pirapora do Bom Jesus Formation, composed of MORB-like tholeiitic metabasalts with pillow-lava structures associated with pyroclastic rocks and meta-limestones showing well-preserved stromatolite structures (Bergmann, 1988).

A study of provenance based on U-Pb dating of zircon in metasandstones and Sm-Nd isotopic data from metamudrocks indicated that the São Roque Group received terrigenous contributions derived mainly from old cratonic areas; no contributions younger than 1.7 Ga were identified (Henrique-Pinto et al., 2015a, 2015b).

ANALYTICAL METHODS

Petrography and whole-rock chemical analyses were reported in a previous work (Henrique-Pinto and Janasi, 2010); readers are referred to that paper for access to data, illustrations and analytical details. U-Pb and Lu-Hf isotope data were obtained at CPGeo, *Instituto de Geociências*, *Universidade de São Paulo*, Brazil, both in a Neptune Laser Ablation Multi Collector Inductively Coupled Plasma Mass Spectrometer (LA-MC-ICPMS) equipped with 9 Faraday detectors, 6 multi-ion counting and 1 secondary electron multiplier. For U-Pb analyses, the laser was operated at 6 Hz repetition rate and 6 mJ power; spot size was 32 µm. Two determinations of zircon reference material GJ-1 (estimated $^{206}Pb/^{238}U$ age of 599.8 ± 4.5 Ma) were done for the correction of U/Pb and Th/U ratios and two determinations of Nist-612 were used for correction of the $^{204}Pb/^{206}Pb$ ratio. For Lu-Hf analyses, conditions were 7 Hz, 6 mJ and spot size 47 µm. Present-day ratios $^{176}Hf/^{177}Hf$ = 0.282772 (CHUR) and 0.283225 (DM); $^{176}Lu/^{177}Hf$ = 0.0332 (CHUR) 0.038512 (DM) were used for calculations of εHf (CHUR values taken from Bichert-Toft and Albarède, 1997; DM values from Vervoort and Bichert-Toft, 1999). Double-stage Hf model ages were calculated using $^{176}Lu/^{177}Hf$ = 0.015 (Vervoort and Patchett, 1996). The measured values of the $^{176}Hf/^{177}Hf$ ratio for the GJ-1 reference material were 0.282063 ± 0.000293 (N = 4, 2σ), in agreement with the recommended value (0.282000 ± 0.000004). Further details can be found in Henrique-Pinto et al. (2015b) and Janasi et al. (2015).

Trace-element analyses of zircon were measured by laser ablation inductively coupled plasma quadrupole mass spectrometer (LA-Q-ICPMS, Agilent Technologies 7700 series Resolution M-50) at the *Laboratoire des matériaux terrestres* (LabMaTer), *Université du Québec à Chicoutimi* (UQAC), Canada. External calibration was performed using the glass standard NIST-610. Zr, measured independently by EMPA, was used as internal standard.

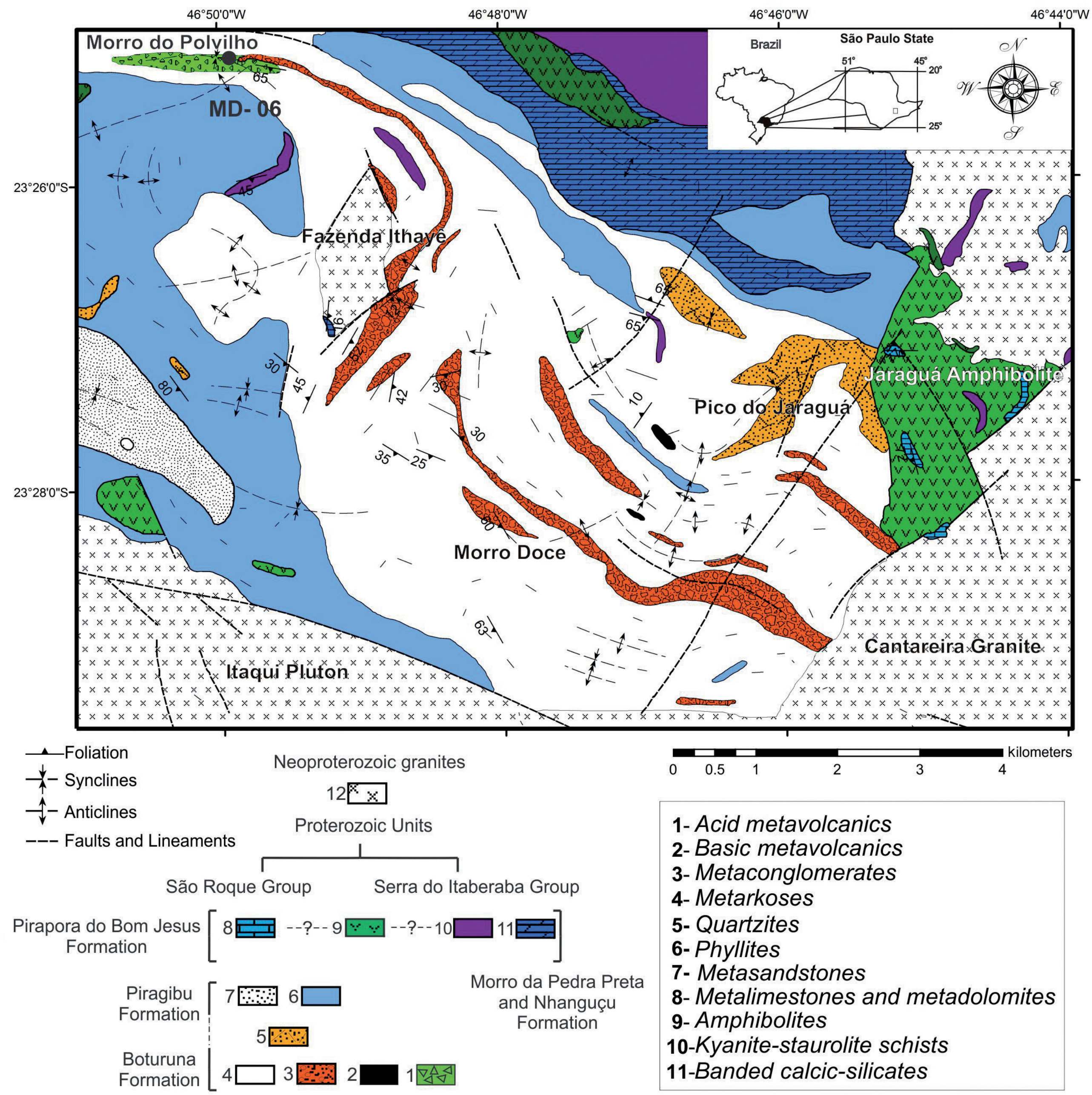
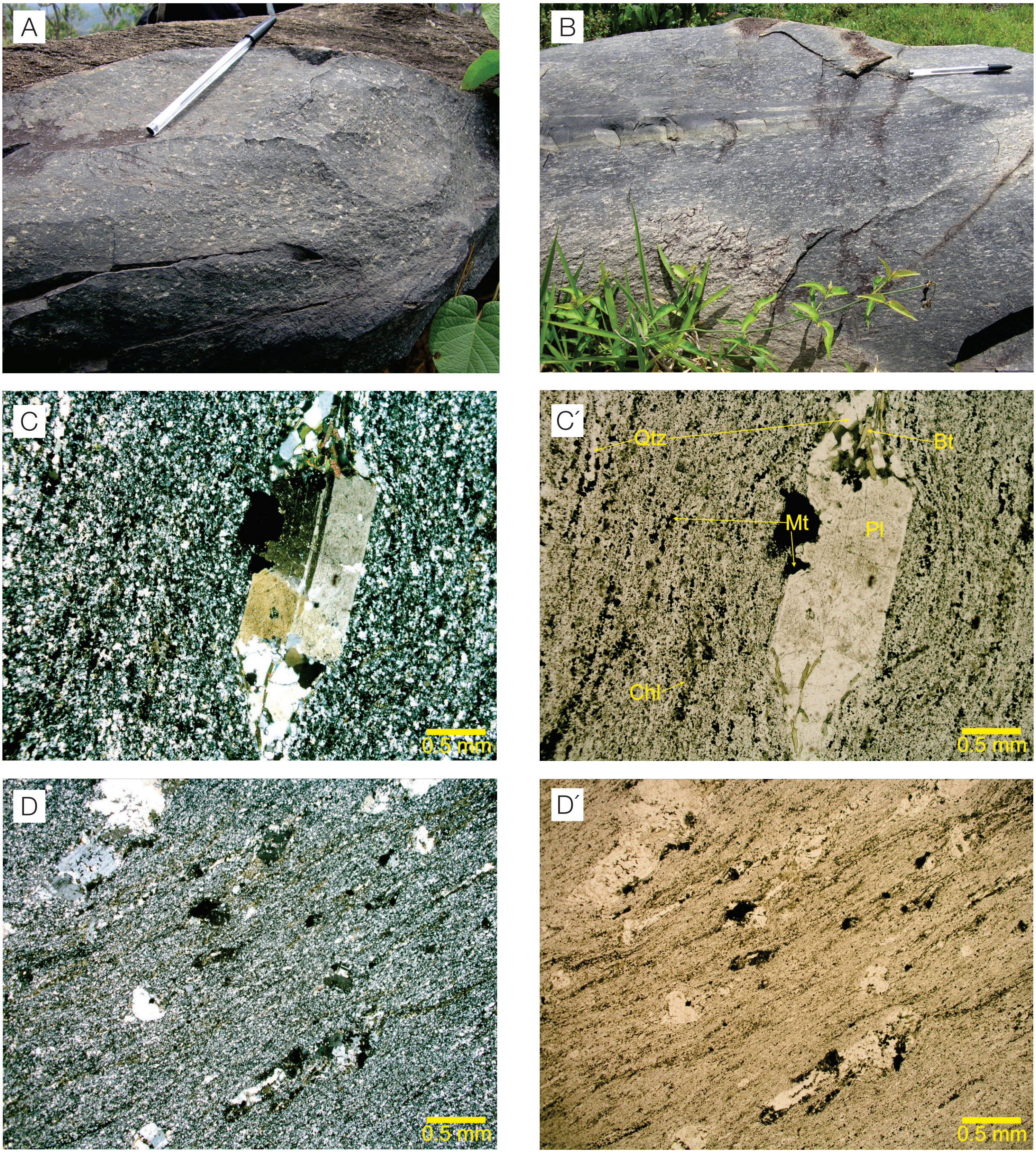


Figure 1. Geological Map for part of the São Roque Domain, including the Morro do Polvilho region, NW of São Paulo city (modified from Henrique-Pinto et al., 2014).

PETROGRAPHY AND GEOCHEMISTRY OF THE POLVILHO META-TRACHYDACITE

Interlayered with terrigenous metasedimentary sequence from Boturuna Formation, the silicic metavolcanic rocks from Morro do Polvilho are porphyritic with ~10% vol. deformed 0.5–1 cm long phenocrysts of sodic plagioclase (oligoclase) that preserve clear evidence of an original idiomorphic shape (Figure 2) set in a fine-grained matrix with small quartz, feldspar and abundant secondary minerals



Qtz: quartz; Bt: biotite; Pl: plagioclase; Chl: chlorite; Mt: magnetite.

Figure 2. Representative field occurrences (A and B) and photomicrographs (C and D) of meta-trachydacite from lower unit of Sao Roque Group (right, crossed polarizers; left, parallel polarizers).

(mostly white mica, epidote and carbonate). Bulk-rock analyses of four samples from Henrique-Pinto and Janasi (2010) indicate relatively homogeneous compositions, with 67–69 wt% SiO_2 (at the trachydacite field in the TAS diagram), high K_2O (up to 5–6 wt%), moderate Na_2O (2.2–3.4 wt%), low Mg# (13–23) and dominantly metaluminous character. High Zr (570–720 ppm) contents are indicative of high magmatic temperatures (T Zr_{sat} = 900-915ºC; model from Watson and Harrison, 1983), within the same range indicated by apatite saturation (T Ap_{sat} = 870–925ºC; model from Harrison and Watson, 1984).

ZIRCON STRUCTURE BY CL

The small to medium (100 to 200 μm) grain size zircons from the meta-trachydacite have euhedral elongated aspect ratio crystals and dominant oscillatory zoning in Cathodoluminescence (Figure 3). These features are commonly found in zircons derived from hydrous granitic magmas (e.g., Pupin, 1980), contrasting with zircon crystallized in high-grade metamorphic rocks with typically rounded shapes and irregular compositional zoning (e.g., Rubatto et al., 2009).

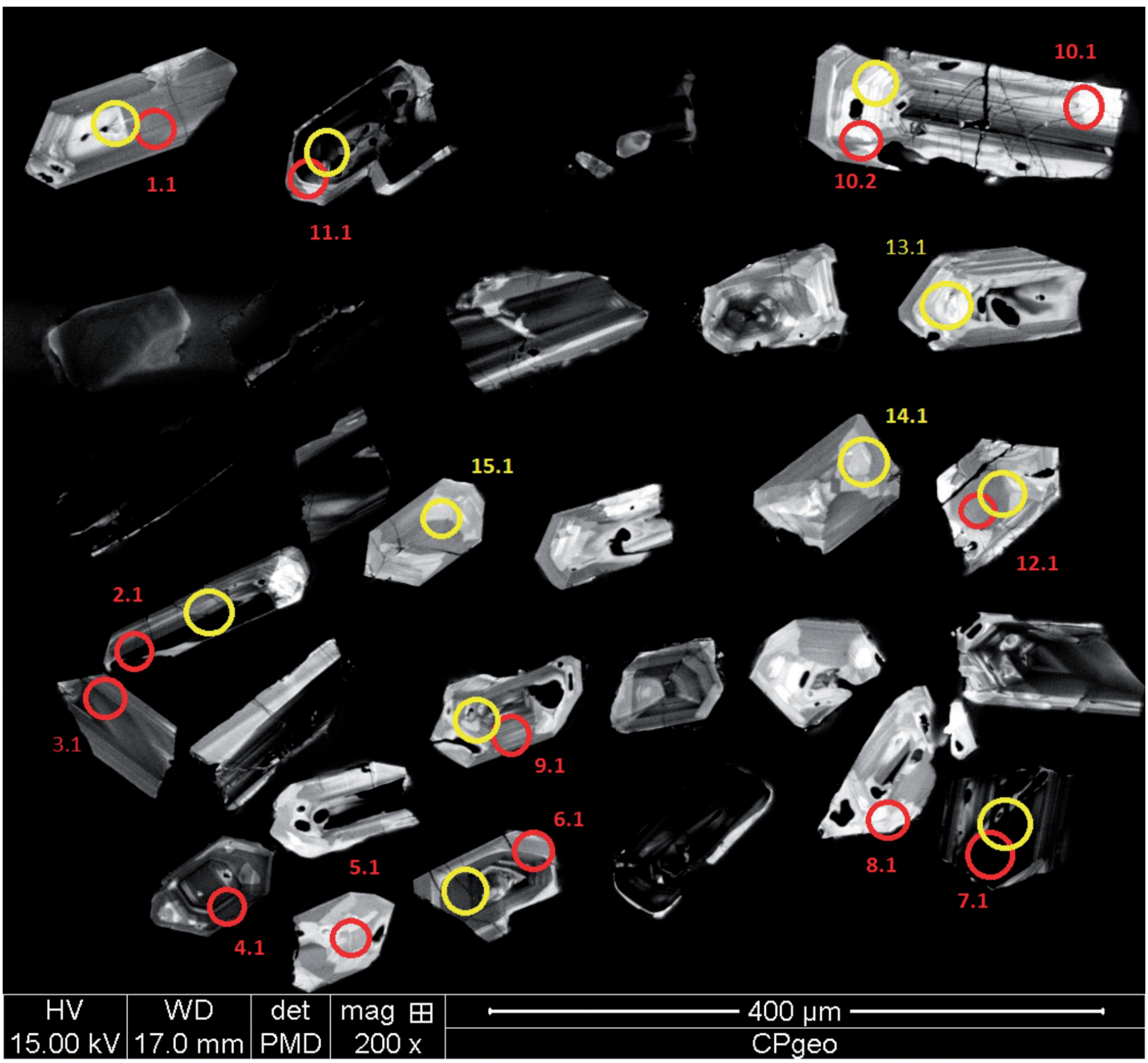


Figure 3. Cathodoluminescence picture of representative zircon crystals from meta-trachydacite of the São Roque Group. Red circles indicate the locals of spot-laser from U-Pb dating and yellow circles the spot-laser of Hf isotope analyses.

Apatite inclusions are common and some crystals have U-depleted cores surrounded by U-rich overgrows (Figure 3; grain 4.1), while others show just the opposite feature (Figure 3; grain 1.1). No inherited crystals were identified, suggesting local co-magmatic compositional changes.

U-PB DATING

Thirteen points were analyzed for U-Pb dating, and the results are shown in Table 1 and Figure 4. All points are close to concordia (10 are > 95% concordant), and no signals of inheritance were found. Using the routines for weighted average of the $^{207}Pb/^{206}Pb$ ages from Ludwig (2012), an age of 1765 ± 45 Ma (95% confidence; internal errors only) is obtained; much lower uncertainty is obtained when using the Tukey's biweight routine, which ignores the assigned errors and weigh them according to their scatter from the mean (1761 ± 14 Ma). A concordia age can be obtained using the 7 most concordant results, and yields a nearly identical value (1760 ± 17 Ma; MSWD = 0.29, probability of concordance = 0.59; Figure 4).

LU-HF ISOTOPES IN ZIRCON

Lu-Hf isotope determination was made on 11 points previously dated. Results are presented in Table 2. Since the grains were large, we could position the 80 µm large points for Lu-Hf analyses avoiding overlapping with the

Table 1. LA-MC-ICPMS U-Pb isotope data for zircons from meta-trachydacite of the São Roque Group.

		RATIOS										
UTM E 313394	UTM N 7408756 spot	207/235	1sigma	206/238	1 sigma	coef. corr	238/206	1 sigma	207/206	1 sigma	208/206	1 sigma
MD - 06	2,1	4,7639	0,1688	0,321	0,0048	0,6	3,1153	0,0461	0,1076	0,004	0,2439	0,0117
MD - 06	4,1	4,7227	0,1656	0,3177	0,0047	0,22	3,1473	0,0463	0,1078	0,0041	0,2203	0,0095
MD - 06	8,1	4,7599	0,2314	0,3193	0,0065	0,55	3,1318	0,0642	0,1081	0,006	0,2427	0,0216
MD - 06	7,1	4,5879	0,1202	0,3089	0,0033	0,65	3,2374	0,0349	0,1077	0,0029	0,2756	0,0103
MD - 06	1,1	4,6149	0,1808	0,3089	0,0051	0,69	3,237	0,0532	0,1083	0,0047	0,2271	0,0273
MD - 06	10,2	4,7739	0,2496	0,3069	0,0071	0,45	3,258	0,075	0,1128	0,007	0,1939	0,0152
MD - 06	9,1	4,6358	0,1879	0,3173	0,0054	0,55	3,1515	0,0533	0,106	0,0048	0,2409	0,0187
MD - 06	5,1	4,259	0,2576	0,2915	0,0072	0,47	3,4304	0,0853	0,106	0,0074	0,1951	0,0186
MD - 06	6,1	4,3562	0,1433	0,2956	0,004	0,83	3,3834	0,0463	0,1069	0,0037	0,2458	0,0099
MD - 06	11,1	4,4462	0,1244	0,2977	0,0034	0,8	3,3596	0,0388	0,1083	0,0031	0,2082	0,0071
MD - 06	12,1	4,5063	0,1756	0,3008	0,0049	0,89	3,3245	0,0544	0,1087	0,0048	0,2181	0,0174
MD - 06	3,1	4,636	0,1544	0,3064	0,0043	0,88	3,2637	0,0459	0,1097	0,0039	0,2506	0,0115
MD - 06	10,1	3,9699	0,2325	0,273	0,0067	0,91	3,6629	0,0894	0,1055	0,0073	0,145	0,0184

RATIOS					AGES				
Pb total comum %	Pb rad ppm	Th ppm	U ppm	Th/U	T206/238	1 sigma	T207/206	1 sigma	Conc. 206/238 207/206
0,35	107,3	250,5	245,8	1,019	1795	0,023	176	0,068	101
0	54,1	137,1	130,9	1,047	1779	0,023	1763	0,071	100
2,6	29,8	53,8	69,1	0,779	1786	0,032	1768	0,101	101
0,14	144,1	288,3	337,9	0,853	1735	0,016	1761	0,049	98
13,34	37,8	62,8	90,6	0,693	1735	0,025	1772	0,08	97
1,16	24,8	32,4	62,7	0,516	1726	0,035	1845	0,113	93
0,6	47,3	86,9	112	0,776	1777	0,026	1731	0,082	102
3,22	20,6	33,4	55,3	0,605	1649	0,036	1731	0,127	95
0,36	60,7	129,3	144,8	0,893	1669	0,02	1747	0,065	95
0,31	76,1	133	194,6	0,683	168	0,017	1772	0,053	94
1,45	30,7	46	79,4	0,579	1695	0,024	1777	0,08	95
0,74	71,2	144,9	166,3	0,871	1723	0,021	1795	0,065	95
0,44	21,5	24,8	58,4	0,425	1556	0,034	1722	0,129	90

holes previously generated by U-Pb dating, but for the majority of grains, still in the same morphological zone. The results are highly uniform, and 10 points have average $^{177}Hf/^{176}Hf = 0.281535 \pm 0.000030$ and $^{177}Lu/^{176}Hf = 0.00099 \pm 0.000099$. Corresponding values of εHf at the magmatic crystallization age (1760 Ma) vary from -4 to -7, with an average of -5.7 ± 1.1. Hf model ages calculated for an "average crust" $^{177}Lu/^{176}Hf = 0.015$ (Vervoort and Patchett, 1996) are 2640–2830 Ma (Figure 5). Point 8.1 has slightly lower $^{177}Hf/^{176}Hf$ and higher $^{177}Lu/^{176}Hf$, and corresponding less negative εHf_t (-1.4) and younger Hf T_{DM} (2475 Ma); it should be noted, however, that the associated errors in measured $^{177}Hf/^{176}Hf$ are about twice the ones obtained in the remaining analyses.

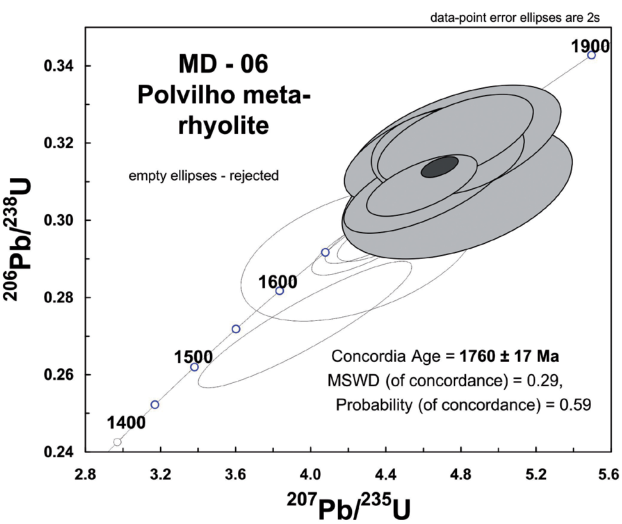


Figure 4. Concordia diagram of zircons from the Morro do Polvilho meta-trachydacite.

ZIRCON TRACE ELEMENTS

In situ trace-element analyses by LA-Q-ICPMS were performed in zircons from the same crystals analyzed for U-Pb and Lu-Hf. Results are presented in Table 3. Five determinations have high La contents, which are accompanied by anomalously high Ba and Sr contents, and are suggested to correspond to portions affected by late hydrothermal alterations and/or to have tiny inclusions of other minerals, being excluded from the following discussion. The other analyses have quite uniform behavior in terms of element ratios, although absolute contents may vary. Average Th/U (0.7) ratio is typical of magmatic zircons and the U/Yb (0.24) ratio is characteristic of zircons crystallized from magmas derived from continental sources (Grimes et al., 2007). Rare-earth elements (REE) patterns are fractionated $(Lu/Sm)_N = 35$, with pronounced negative Eu anomalies ($Eu_N/Eu_N^* = 0.14$) and moderate positive Ce anomalies ($Ce_N/Ce_N^* = 5.8$), suggesting a crystallization from relatively reduced magmas. Compared to the REE patterns of zircons from nearby Neoproterozoic granites (Andrade, 2016), they contrast sharply with those of oxidized high-K calc-alkaline granites, and are similar to those of reduced, fractionated peraluminous granites with "A-type" signature such as the Tico-tico leucogranite (Figure 6).

DISCUSSION

The LA-ICPMS U-Pb zircon concordia age of 1760 ± 17 Ma obtained for the Polvilho meta-trachydacite in this study confirms previous determinations by ID-TIMS U-Pb in two slightly discordant zircon fractions dated by van

Table 2. LA-MC-ICPMS Lu-Hf isotope data for zircons from meta-trachydacite of the São Roque Group.

Grain /spot	Age (t, Ma)	176Hf/177Hf	± 2 se 1,E+06	176Lu/177Hf	± 2 se 1,E+06	176Hf/177Hf (t)	εHf(0)	εHf (t)	Hf T(DM) (Ga)
1,1	1760	0,281565	24	0,000526	2	0,281547	-42,69	-4,11	2648
2,1	1760	0,281528	28	0,000967	17	0,281496	-43,98	-5,92	2763
3,1	1760	0,281504	47	0,001048	48	0,281469	-44,85	-6,90	2825
4,1	1760	0,281521	31	0,000728	13	0,281497	-44,24	-5,90	2762
5,1	1760	0,281505	33	0,001066	6	0,281469	-44,82	-6,88	2824
6,1	1760	0,281497	28	0,000935	4	0,281465	-45,11	-7,02	2832
7,1	1760	0,281534	31	0,000818	7	0,281507	-43,77	-5,53	2739
8.1	1760	0,281678	78	0,001607	47	0,281624	-38,70	-1,39	2475
9.1	1760	0,281547	40	0,001382	18	0,281500	-43,33	-5,77	2753
10.1	1760	0,281588	36	0,001071	28	0,281552	-41,88	-3,94	2637
11.1	1760	0,281563	40	0,001336	27	0,281518	-42,77	-5,15	2714
average		0,281548	38	0,001044	20	0,281513	-43,29	-5,32	2725
1 sigma		0,000052	15	0,000309	16	0,000047	1,8	1,7	105

Schums et al. (1986) and defines the age of deposition of the associated metaconglomerate-metarkose sequence of the São Roque Group. Field evidence favors an origin as rhyolitic deposits of effusive or pyroclastic nature interlayered with metaconglomerates bearing granite pebbles dated at 2.2 Ga (Henrique-Pinto et al., 2012). As direct observation of contacts is not possible, the alternative interpretation that the rhyolites are concordant intrusive bodies cannot be totally ruled out. In this case, the 1.76 Ga age would constitute an upper limit for deposition of the metasedimentary sequence. The presence of detrital zircons with similar age in the associated metarenites and metarkoses (Henrique-Pinto et al., 2015b), constrains the lower limit of deposition to be close to the upper limit, and therefore the meta-trachydacite U-Pb zircon age is also conclusively dating the depositional age at least to the basal units of the sequence (Boturuna Formation).

The Polvilho meta-trachydacite zircons have slightly negative εHf(t), indicating that the parent melts had a crustal component. These values are on average less negative than the detrital zircons of the same age found in the associated metasedimentary sources [author's unpublished data; see

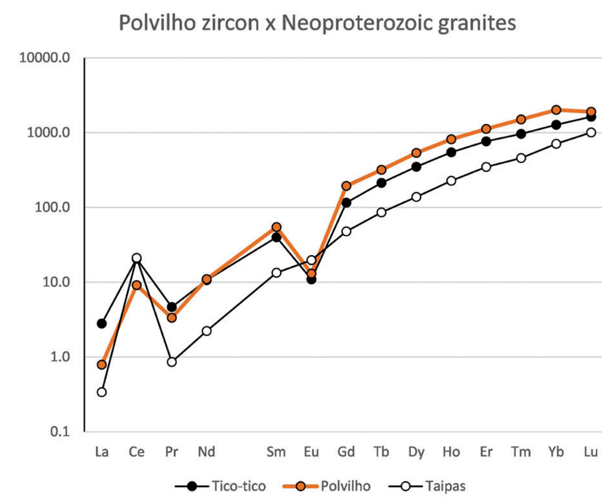


Figure 6. Chondrite-normalized REE patterns of the median of 11 analyses of zircon from the Morro do Polvilho meta-trachydacite (this work) compared to typical high-K calc-alkaline (Taipas) and fractionated "A-type" (Tico-tico) Neoproterozoic granites from the São Roque Domain (data from Andrade, 2016).

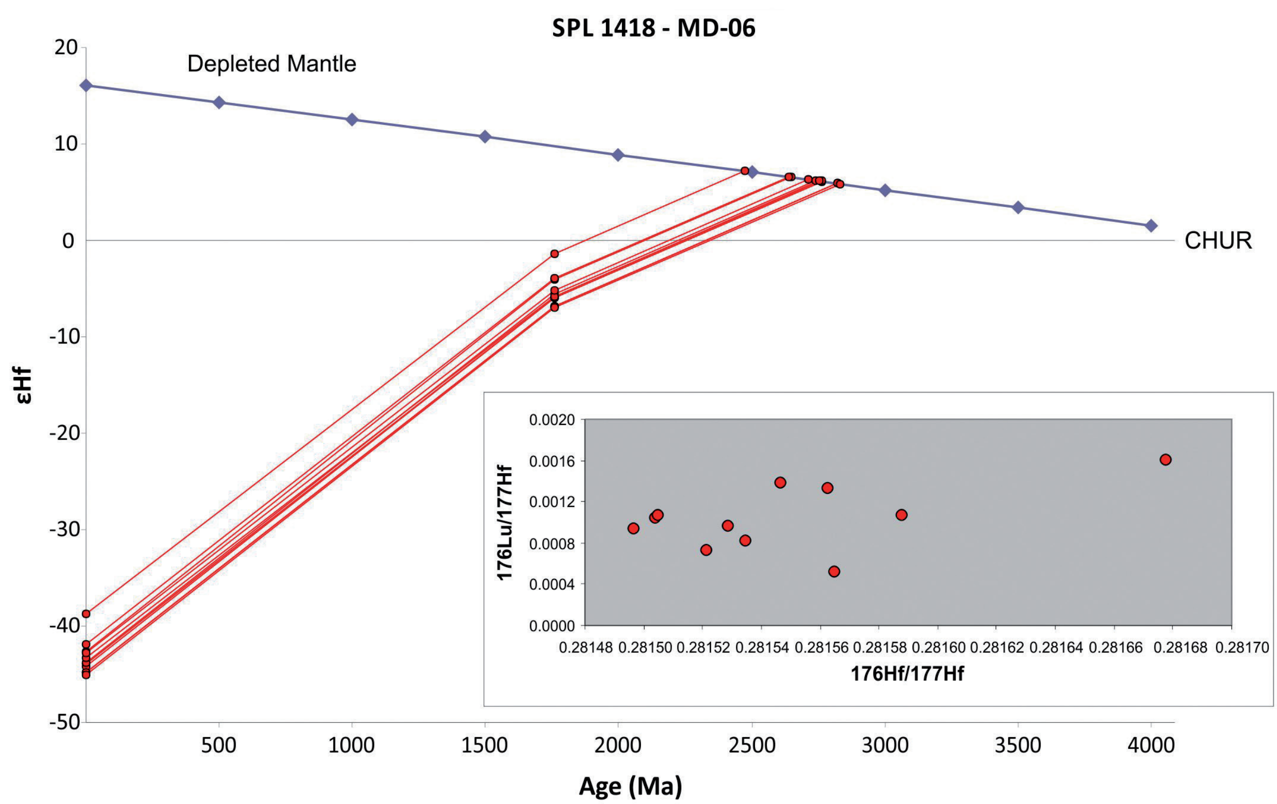


Figure 5. εHf × time diagram for zircons from the Morro do Polvilho meta-trachydacite; double stage evolution admitting $^{177}Lu/^{176}Hf = 0.015$ for the source from magmatic age up to DM.

Table 3. Representative trace element LA-ICPMS analyses of zircons from meta-trachydacite of the São Roque Group.

ppm	Si	Zr	Hf	Ba	Sr	Na	Mg	Al	P	Sc	Fe	Ga	Y	Nb	Ta	Th	U
MD06-1.D	161892	478989	9026	0,48	1,04	24,4	34,4	73,5	117	629	107	0,35	1137	23,6	1,01	38,0	81,2
MD06-1.D	164757	481377	8558	0,91	0,90	38,7	1,2	47,8	169	631	37,2	0,35	993	23,4	1,06	38,4	64,5
MD06-2.D	165235	472781	9026	0,19	0,87	9,7	2,6	20,5	105	659	43,0	0,15	583	21,2	0,91	23,9	55,4
MD06-2.D	164280	489973	8357	0,96	2,05	5,3	16,7	44,4	673	683	134	2,82	1705	24,0	2,04	114	148
MD06-2.D	153773	476124	8739	7,64	1,77	62,1	2,6	649	244	616	21,5	2,96	678	24,9	1,04	29,9	50,1
MD06-3.D	162847	480900	8629	3,34	1,14	21,5	4,4	138	134	612	37,2	0,57	1495	21,8	1,02	52,9	70,0
MD06-4D.D	160937	475647	8816	0,16	2,15	12,8	5,4	49,7	219	638	59,2	1,26	3243	28,5	3,10	251	283
MD06-5.D	162847	472304	8305	0,10	1,96	13,4	21,0	43,5	516	619	75,0	1,81	2369	23,8	1,81	110	140
MD06-6.D	163324	486630	12034	1,72	3,63	11,8	15,8	81,2	405	637	134	3,06	4136	41,5	3,42	1098	615
MD06-7.D	170488	458932	8501	0,43	0,76	6,2	5,5	17,3	181	591	44,9	0,34	793	22,2	1,19	32,2	59,2
MD06-7.D	144222	453201	8491	0,36	0,99	12,3	2,9	24,0	222	588	53,5	0,57	1514	24,0	1,54	94,1	106
MD06-8.D	159504	482810	8477	0,13	0,98	5,3	1,6	17,8	160	619	30,6	0,46	1189	22,4	1,06	46,3	62,2
MD06-9.D	159982	475169	8658	0,19	0,98	8,4	1,0	25,8	140	632	37,2	0,38	1256	24,0	1,08	49,2	68,8
MD06-10.D	160937	484720	9360	2,39	1,32	33,4	71,6	210	138	607	210	0,76	1605	23,9	1,20	72,6	114
MD06-11.D	152341	493794	8262	0,32	1,48	7,4	7,3	25,8	242	635	38,7	0,60	2679	22,4	1,74	117	136
MD06-12.D	149953	484720	8200	0,11	1,42	20,5	2,9	18,0	168	614	38,7	0,72	1987	21,7	1,25	79,3	95,0

ppm	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
MD06-1.D	0,07	5,36	0,19	2,18	5,92	0,62	29,2	9,17	113	39,78	168	36,0	344	48,8
MD06-1.D	0,62	6,26	0,28	3,20	4,78	0,51	25,5	8,40	98,4	35,00	144	29,2	278	39,5
MD06-2.D	0,04	3,66	0,13	1,43	2,48	0,51	14,4	5,21	61,6	21,25	89,8	21,4	185	25,4
MD06-2.D	20,1	52,5	6,69	38,7	17,7	1,86	61,1	16,0	177	61,13	243	49,2	439	59,7
MD06-2.D	24,8	49,2	4,39	20,1	5,25	0,49	17,8	5,40	62,1	22,64	97,9	21,2	190	27,9
MD06-3.D	0,31	6,28	0,51	7,59	11,60	1,29	48,7	14,9	166	54,82	213	43,2	377	53,8
MD06-4D.D	0,13	20,6	0,64	11,22	19,4	0,72	102	32,3	355	120,3	468	95,8	786	110
MD06-5.D	6,69	25,3	2,87	26,7	21,0	1,91	82,1	24,1	267	88,83	345	68,1	574	81,8
MD06-6.D	8,12	66,9	1,81	12,9	18,7	0,81	91,6	33,0	425	153,3	644	145,7	1270	202
MD06-7.D	0,04	4,96	0,06	1,34	2,48	0,35	19,9	6,64	74,0	26,70	111	23,1	243	34,2
MD06-7.D	0,21	9,41	0,27	5,68	9,26	0,64	48,2	15,0	161	53,96	230	44,4	372	57,9
MD06-8.D	0,13	5,97	0,36	5,44	8,12	0,96	37,2	11,6	128	43,94	179	36,4	320	47,9
MD06-9.D	0,22	5,92	0,33	5,30	8,93	1,04	40,6	12,2	143	48,71	193	40,1	352	51,1
MD06-10.D	0,53	9,60	0,68	7,69	11,4	1,02	49,2	14,8	170	57,12	241	47,7	444	60,3
MD06-11.D	1,62	11,9	1,32	13,1	18,4	1,47	85,5	25,7	290	98,90	385	74,2	619	93,6
MD06-12.D	0,29	9,69	0,52	9,60	13,8	1,50	70,7	20,9	220	73,07	287	55,7	488	72,0

also Janasi et al. (2015)], suggesting that the parent melt derived from a source with lower crustal residence or that a "juvenile" component was added to the source, generating the detrital zircons.

The trace-element chemistry of the zircon is very characteristic of magmas generated from crustal sources and, together with the whole-rock chemistry, is consistent with generation in a within-plate tectonic setting, as it has clear similarities with high-temperature A-type granites of reduced character, as indicated by pronounced negative Eu anomalies (average $Eu_N/Eu^* = 0.14$) and moderate positive Ce anomalies.

These results are in accordance with those by Henrique-Pinto et al. (2015a, 2015b), which suggested an intraplate environment for the lower Boturuna Formation, deposited in the Statherian with sources in an old cratonic region. However, the age of other units from the São Roque Domain remains to be established through precise dating by modern techniques. It seems particularly important to define the stratigraphic status of the Pirapora do Bom Jesus Formation, interpreted by some authors as part of a Neoproterozoic back-arc basin (e.g., Hackspacher et al., 2000) or as an ophiolite slice, in view of the important volume of mafic magmatic rocks with pillow lavas, MORB-type chemistry and association with magnetite/chromite-talc schists (Tassinari et al., 2001).

CONCLUSIONS

The age of the Polvilho meta-trachydacite was firmly established at 1760 ± 17 Ma, and dates the deposition of the lower terrigenous-metavolcanic Boturuna Formation of the São Roque Group, confirming that it is older than the higher-metamorphic grade sequences of the neighboring Serra do Itaberaba Group. The Hf isotope signature and chemistry of the zircons indicates that the parent melts derive from old continental crust. This crust was melted in a within-plate environment, as indicated by the bimodal character of volcanism, whole-rock chemistry and trace-element chemistry of zircon, typical of high-temperature melts (e.g., zircon saturation temperatures ~ 900ºC) derived from continental sources under reducing conditions.

ACKNOWLEDGEMENTS

Fapesp 2012/04148-0 and 2015/01817-6, CNPq Productivity scholarship to VAJ, Valter Sproesser, Solange Lucena de Souza, Miguel Basei at CPGeo for support with obtaining U-Pb and Lu-Hf isotope data. We also thank Dany Savard and Sarah J-Barnes at LabMaTer for support with obtaining trace-element analyses of zircon.

REFERENCES

Andrade, S. (2016). *Análises por LA-ICPMS em zircões de rochas graníticas da Faixa Ribeira no Estado de São Paulo-SE do Brasil: implicações genéticas e geocronológicas*. Tese (Doutorado). São Paulo: Universidade de São Paulo, 361 p.

Bergmann, M. (1988). *Caracterização Estratigráfica e Estrutural da Sequência Vulcano-Sedimentar do Grupo São Roque na Região de Pirapora do Bom Jesus – Estado de São Paulo.* Dissertação (Mestrado). São Paulo: Instituto de Geociências, Universidade de São Paulo.

Bichert-Toft, J., Albarède, F. (1997). The Lu–Hf isotope geochemistry of chondrites and the evolution of the mantle–crust system. *Earth and Planetary Science Letters*, 148, 243-258. https://doi.org/10.1016/S0012-821X(97)00040-X

Campanha, G. A. C., Basei, M. S., Faleiros, F. M., Nutman, A. P. (2016). The Mesoproterozoic to early Neoproterozoic passive margin Lajeado Group and Apiaí Gabbro, Southeastern Brazil. *Geoscience Frontiers*, 7(4), 683-694. https://doi.org/10.1016/j.gsf.2015.08.004

Campanha, G. A. C., Basei, M. S., Tassinari, C. C. G., Nutman, A. P., Faleiros, F. M. (2008). Constraining the age of the Iporanga Formation with SHRIMP U-Pb zircon: Implications for possible Ediacaran glaciation in the Ribeira Belt, SE Brazil. *Gondwana Research*, 13(1), 117-125. http://dx.doi.org/10.1016/j.gr.2007.05.010

Campanha, G. A. C., Faleiros, F. M., Basei, M. A. S., Tassinari, C. C. G., Nutman, A. P., Vasconcelos, P. M. (2015). Geochemistry and age of mafic rocks from the Votuverava Group, southern Ribeira Belt, Brazil: Evidence for 1490 Ma oceanic back-arc magmatism. *Precambrian Research*, 266, 530-550. http://dx.doi.org/10.1016/j.precamres.2015.05.026

Campos Neto, M. C. (2000). Orogenic Systems from Southwestern Gondwana: an Approach to Brasiliano-Pan African Cycle and Orogênic Collage in Southeastern Brazil. *XXXI International Geological Congress*, 335-365. Rio de Janeiro, Brazil.

Grimes, C. B., John, B. E., Kelemen, P. B., Mazdab, F. K., Wooden, J. L., Cheadle, M. J., Hanghøj, K., Schwartz, J. J. (2007). Trace element chemistry of zircons from oceanic crust: a method for distinguishing detrital zircon provenance. *Geology*, 35, 643-646. https://doi.org/10.1130/G23603A.1

Hackspacher, P. C., Dantas, E. L., Spoladore, A., Fetter, A. H., Oliveira, M. A. F. (2000). Evidence of neoproterozoic backarc basin development in the Central Ribeira Belt, southeastern Brazil: new geochronological and geochemical contraints from the São Roque-Açungui groups. *Revista Brasileira de Geociências*, 30(1), 110-114.

Harrison, T. M., Watson, E. B. (1984). The behavior of apatite during crustal anatexis: equilibrium and kinetic considerations. *Geochimica et Cosmochimica*, 48, 1467-1477. https://doi.org/10.1016/0016-7037(84)90403-4

Hasui, Y., Sadowski, G. R., Carneiro, C. D. R. (1976). Considerações sobre a estratigrafia do pré-Cambriano na região de São Paulo. *Boletim do Instituto de Geociências, USP*, 7, 107-112.

Henrique-Pinto, R., Janasi, V. A. (2010). Metaconglomerados e rochas associadas do Grupo São Roque a norte da cidade de São Paulo, Brasil. *Revista Brasileira de Geociências*, 40(3), 409-425.

Henrique-Pinto, R., Janasi, V. A., Carvalho, B. B., Calado, B. O., Grohmann, C. H. (2014). Integrated geological map of the São Roque Domain, North of São Paulo City - Brazil. *Journal of Maps*, 434-439. https://doi.org/10.1080/17445647.2014.883338

Henrique-Pinto, R., Janasi, V. A., Simonetti, A., Tassinari, C. C. G., Heaman, L. M. (2012). Paleoproterozoic source contributions to the São Roque Group sedimentation: LA-MC-ICPMS U-Pb dating and Sm-Nd systematics of clasts from metaconglomerates of the Boturuna Formation. *Geologia USP. Série Científica*, 12(3), 21-32. https://doi.org/10.5327/Z1519-874X2012000300002

Henrique-Pinto, R., Janasi, V. A., Tassinari, C. C. G., Carvalho, B. B., Cioffi, C. R., Stríkis, N. M. (2015a). Provenance and sedimentary environments of the Proterozoic São Roque Group, SE-Brazil: Contributions from petrography, geochemistry and Sm–Nd isotopic systematics of metasedimentary rocks. *Journal of South American Earth Sciences*, 63, 191-207. https://doi.org/10.1016/j.jsames.2015.07.015

Henrique-Pinto, R., Janasi, V. A., Vasconcellos, A. C. B. C., Sawyer, E. W., Barnes, S. J., Basei, M. A. S., Tassinari, C. C. G. (2015b). Zircon provenance in meta-sandstones of the São Roque Domain: Implications for the Proterozoic evolution of the Ribeira Belt, SE Brazil. *Precambrian Research*, 256, 271-288. https://doi.org/10.1016/j.precamres.2014.11.014

Janasi, V. A., Andrade, S., Vasconcellos, A. C. B. C., Henrique-Pinto, R., Ulbrich, H. H. G. J. (2015). Timing and sources of granite magmatism in the Ribeira Belt, SE Brazil: Insights from zircon in situ U–Pb dating and Hf isotope geochemistry in granites from the São Roque Domain. *Journal of South American Earth Sciences*, 68, 224-247. https://doi.org/10.1016/j.jsames.2015.11.009

Juliani, C., Beljavskis, P. (1995). Revisão da litoestratigrafia da faixa São Roque/Serra do Itaberaba - SP. *Revista do Instituto Geológico*, 16, 33-58. http://dx.doi.org/10.5935/0100-929X.19950003

Juliani, C., Hackspacher, P. C., Dantas, E. L., Fetter, A. H. (2000). The Mesoproterozoic volcano-sedimentary Serra do Itaberaba Group of the Central Ribeira Belt, São Paulo State, Brazil: implications for the age of the overlying São Roque Group. *Revista Brasileira de Geociências*, 30(1), 82-86.

Juliani, C., Martin, M. A. B., Clarimundo, J. (1997). Os metarcoseos do Morro do Polvilho: implicações para geocronologia e para evolução crustal dos grupos Serra do Itaberaba e São Roque (SP). *Anais da Academia Brasileira de Ciências*, 69, 441.

Ludwig, K.R. (1992). ISOPLOT – a plotting and regression program for radiogenicisotope data, version 2.57, *U.S. Geological Survey, Open-File Report*, 91, 445.

Pupin, J. P. (1980). Zircon and granite petrology. *Contributions to Mineralogy and Petrology*, 73(3), 207-220. http://dx.doi.org/10.1007/BF00381441

Rubatto, D., Hermann, J., Berger, A., Engi, M. (2009). Protracted fluid-induced melting during Barrovian metamorphism in the Central Alps. *Contributions to Mineralogy and Petrology*, 158(6), 703-722. https://doi.org/10.1007/s00410-009-0406-5

Siga Jr., O., Basei, M. A. S., Sato, K., Passarelli, C. R., Nutman, A., McReath, I., Prazeres Filho, H. J. (2011). Calymmian (1.50-1.45 Ga) magmatic records in Votuverava and Perau sequences, south-southeastern Brazil: Zircon ages and Nd-Sr isotopic geochemistry. *Journal of South American Earth Sciences*, 32(4), 301-308. https://doi.org/10.1016/j.jsames.2011.03.015

Tassinari, C.C.G., Munhá J.M.U., Ribeiro, A., Correia, C.T. (2001). Neoproterozoic oceansin the Ribeirrrrra Belt (southeastern Brazil): the Pirapora do Bom Jesus ophioliticcomplex. *Episodes*, 24 (4), 245-250.

Taylor, S.R., McLennan, S.M. (1985) *The Continental Crust:* Its Composition and Evolution: An Examination of the Geochemical Record Preserved in Sedimentary Rocks. Oxford, Blackwell Science, 312 p.

van Schums, W. R., Tassinari, C. C. G., Cordani, U. (1986). Estudo geocronológico da parte inferior do Grupo São Roque. *XXXIV Congresso Brasileiro de Geologia*, Anais, 1399-1406. Goiânia: Sociedade Brasileira de Geologia.

Vervoort, J. D., Blichert-Toft, J. (1999). Evolution of the depleted mantle: Hf isotope evidence from juvenile rocks through time. *Geochimica et Cosmochimica*, 63(3-4), 533-556. https://doi.org/10.1016/S0016-7037(98)00274-9

Vervoort, J. D., Patchett, P. J. (1996). Behavior of hafnium and neodymium isotopes in the crust: constraints from Precambrian crustally derived granites. *Geochimica Cosmochimica*, 60(19), 3717-3733. https://doi.org/10.1016/0016-7037(96)00201-3

Watson, E. B., Harrison, T. M. (1983). Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types. *Earth and Planetary Science Letters*, 64(2), 295-304. https://doi.org/10.1016/0012-821X(83)90211-X