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Zircon ages delimit the provenance of a sand extrudite from the Botucatu Formation in the Paraná volcanic province, Iraí, Brazil

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ABSTRACT

Ion microprobe age determinations of 102 detrital zircon crystals from a sand extrudite, Cretaceous Paraná volcanic province, set limits on the origin of the numerous sand layers present in this major flood basalt province. The zircon U-Pb ages reflect four main orogenic cycles: Mesoproterozoic (1155-962 Ma), latest Proterozoic-early Cambrian (808-500 Ma) and two Palaeozoic (Ordovician– 480 to 450 Ma, and Permian to Lower Triassic– 296 to 250 Ma). Two additional small concentrations are present in the Neoarchean (2.8 to 2.6 Ga) and Paleoproterozoic (2.0 to 1.7 Ga). Zircon age peaks closely match the several pulses of igneous activity in the Precambrian Brazilian Shield and active orogeny in Argentina. A main delimitation of the origin of the sand is the absence of zircon ages from the underlying Cretaceous basalts, thus supporting an injectite origin of the sand as an extrudite that emanated from the paleoerg that constitutes the Botucatu Formation.

Key words: Botucatu Formation, Brazil, Neoarchean to Palaeozoic ages, provenance, sand extrudite, Zircon U-Pb ages.

INTRODUCTION

Detrital minerals in sedimentary rocks provide a record of the provenance of the rocks and are a clue to the tectonic processes in the source terranes. Zircon is a prominent component of detrital assemblages, because it is highly refractory and resilient, occurring in nearly all sedimentary deposits and thus providing a critical link between source terranes and the final sedimentary repository (Fedo et al. 2003). The use of detrital zircon U-Pb ages obtained by the sensitive high resolution ion microprobe (SHRIMP) is a powerful tool in the provenance investigation of sedimentary rocks (Hartmann et al. 2004, 2008, Najman 2006, Santos et al. 2002, 2003).

Sandstone layers (1-5 m thick, 100-500 m large) are very common in the Paraná volcanic province (e.g. Hartmann et al. 2012, 2013) of southeastern South America (mostly Brazil, but also Uruguay, Argentina and Paraguay). There may be up to 120 layers in each stratigraphic column of basalts and rhyodacites of this bimodal province, because a layer is present between nearly every two successive lava flows. Numerous sandstone feeder dikes and sills are also present. The composition of the sandstone is

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mostly quartz (90 vol.%), feldspar (5%) and opaque minerals (5%), with a chalcedony cement.

We selected a silicified sandstone layer near Iraí, state of Rio Grande do Sul, Brazil, because it is positioned nearly 800 m above the contact of the volcanic province and the underlying paleoerg (Botucatu Formation). The origin of this layer is likely similar to the many other sandstone layers in the volcanic province, which makes this a most significant study in the realm of sedimentary and volcanic processes in their interaction in a large intraplate basaltic province.

The regional geology presents a major puzzle, with the presence of strongly silicified sandstones intercalated in basalts of a major continental volcanic province. The detrital grains (mostly quartz, some feldspar) are similar to the grains present in the Botucatu Formation paleoerg below the volcanics and no surficial source for the quartz is present in the Serra Geral Group.

The SHRIMP U-Pb analysis of zircon crystals was used to determine the age of the detrital grains with the goal of delimiting the provenance and origin of the sandstone layers in the Paraná volcanic province.

MATERIALS AND METHODS

The sample of silicified sandstone was collected for SHRIMP studies in a rock cut of BR386 highway, close to Iraí town in the section that continues to Frederico Westphalen (Figs. 1a, 1b, 1c, 1d). The sample is from a sandstone layer that covers the basalt flow dated by Pinto et al. (2011) from the same outcrop. The quartz sandstone has rounded and well selected quartz (~90%), orthoclase (~4%), plagioclase (3%), and muscovite (3%) with epidote, zircon, apatite, titanite and magnetite as main accessories. The sample weighing 2 kg was crushed, milled, processed by sieving and heavy liquid and magnetic mineral separation at the Universidade Federal do Rio Grande do Sul laboratories. Zircon was hand-picked at the final stage.

Selected grains were mounted on an epoxy disc with chips of the BR266 zircon standard, ground and polished until nearly half of each grain was removed, and then microphotographed in transmitted and reflected light. For visualization of internal morphology, imaging was performed at the University of Western Australia using a scanning electron microscope (i.e. backscattered electrons). The mount was then cleaned and gold-coated to have a uniform electrical conductivity during the SHRIMP analyses.

The isotopic composition of the zircons was determined with the Curtin University SHRIMP II equipment, using methods described by Compston et al. (1992) and Smith et al. (1998). Circular areas of 20-30 μm were analyzed from morphologically distinct zones chosen within zircon grains and replicate analyses of the BR266 standard in the same epoxy mount. Corrections for common Pb were made using measured ^{204}Pb and the Pb isotopic composition. Results with more than 1% common lead correction were not used to calculate the ages, such as grains C3-5 and D14-4 (Table SI) (Supplementary Material). For each analysis, an initial 60-90 seconds were used to rasterize and remove the gold, avoiding the analysis of common Pb from the coating. Zircon data are reduced using SQUID (Ludwig 2002). Data were plotted on weighted average using ISOPLOT/Ex software (Ludwig 1999). The uncertainty in all pooled ages is at the 95% confidence levels, whereas errors in Table SI are at 1 sigma (%). Ages older than 1.5 Ga are expressed as weighted mean ^{207}Pb/^{206}Pb age values, and younger ages are based on weighted mean ^{206}Pb/^{238}U ratios.

GEOLOGICAL SETTING

The Paraná volcanic province extends for approximately 917,000 km^2 (Frank et al. 2009) near the top of the Paraná Basin (Zalán et al. 1991), only overlain partly by the Bauru Group of sedimentary rocks. The province is made up mostly of the Serra Geral Group of bimodal basalt-rhyodacite rocks (e.g. Pinto and Hartmann 2011). The thickness of lavas in the depocenter of the basin (100 km to

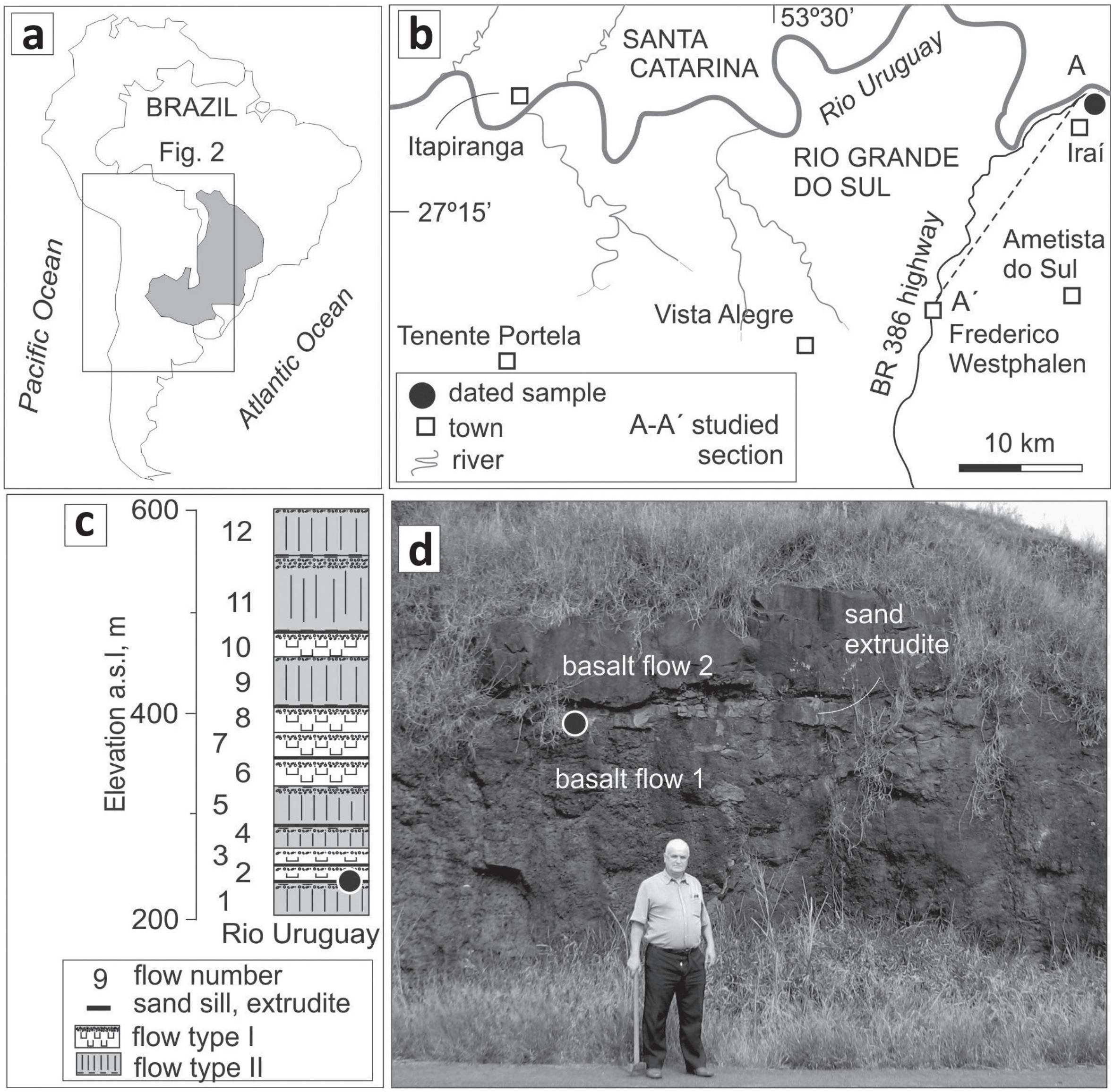

Figure 1 - Location map: **a)** map of South America and Brazil highlighting the Paraná Basin; **b)** study region indicating the sampling section; **c)** location of the collected sandstone in the stratigraphic section; **(d)** outcrop indicating site of collected sample; flows type 1 and type 2 from Pinto et al. (2011).

the north of the studied outcrop) reaches 1,800 m, corresponding possibly to 120 flows.

The climate seems to have remained arid during the entire event of lava effusion, because the volcanic group is underlain by the aeolian erg deposits of the Botucatu Formation and overlain by sedimentary rocks formed in a desert environment. No evidence of humid climate is registered in lava structure or lava stratigraphy.

Intertrap aeolian sandstone deposits occur on top of the first few lava flows in many sections of the province. Higher up in the volcanic stratigraphy, sandstones with low-angle stratification are common along the entire sequence, both horizontally and vertically. Sandstone dikes and sills are also common; dikes are feeder conduits to the sandstone layers. Although interpreted previously as wind-blown sand deposits over basalt flows, the sandstones are now described as an injectite complex made up of a source layer in the paleoerg (Botucatu Formation), an injectite complex of dikes and sills and extrudites at the paleosurface (Hartmann et al. 2012).

In Iraí, a stratigraphic section of 13 basalt lava flows, initiating in Iraí and reaching Frederico Westphalen (Pinto and Hartmann 2011), has the composition of high-Ti near the level of Rio Uruguay (Fig. 1). The lavas evolve into medium-Ti Paranapanema chemical type as defined by Peate et al. (1992) for the entire province. Every lava flow has a strongly silicified sandstone (0.3-1.0 m thick) layer on top and is intruded by thin (0.1-0.3 m) dikes of similar composition. The studied sample was collected from a flat-lying sandstone layer at the bottom of the sequence near Iraí (Figs. 1c, 1d).

The paleoerg Botucatu Formation is distributed over an area larger than 1,500,000 km^2 (Scherer and Goldberg 2007), possibly the largest sand sea in Earth history. Both the volcanic rocks and the underlying paleoerg are also present in the Etendeka (Stanistreet and Stollhoffen 1999), the African fragment of the pre-rifting basin. The concordant contact and interlayering of the Botucatu Formation and the Serra Geral Group means that the lavas flowed initally over loose, non lithified dune sand.

The age of volcanism in the province is close to 135 Ma, based on Ar-Ar isotopes (Thiede and Vasconcelos 2010), U-Pb zircon SHRIMP (Pinto et al. 2011) and SIMS (Janasi et al. 2011). The duration of lava effusion is commonly considered to be less than one million years. The intimate relationship between the aeolian sandstones and the lava flow deposits, and the lack of regional-scale unconformities within the aeolian package suggest that the Botucatu Formation comprises a shorter time interval, as discussed by Scherer (2000). Therefore, the beginning of Cretaceous age, probably Valanginian, seems more adequate for the onset of aeolian sedimentation in the Botucatu Formation.

The Brazilian Shield underneath the Paraná Basin (Fig. 2) is composed of igneous and metamorphic rocks of the Brasiliano orogenic cycle (880-500 Ma; e.g. Silva et al. 2005) and of the Rio de La Plata craton (mostly Trans-Amazonian Cycle 2.35-2.00 Ga) with lesser Archean rocks (e.g. Hartmann et al. 2000, 2008, Santos et al. 2002).

The regional and local geology require adequate techniques of investigation to solve the puzzle of the presence of quartz sandstone layers on top of basalt flows in the entire province and in Iraí. Zircon dating is considered appropriate.

AGE DATA

One hundred and two zircon grains were dated by U-Pb SHRIMP II, using between three and five scans for each grain. The sample was divided in two populations named C and D, with C1-C10 and D11-D25 sub-populations (Table SI). All obtained data are shown in Table SI and representative populations in Figure 3a. The main population (Fig. 3b) is represented by fifty grains of the Brasiliano Cycle (810–503 Ma) age and the second group is from seventeen grains of Sunsás Cycle (1100–960 Ma) age. Other important groups (Fig. 3c) are ten grains aged ~480-440 Ma (Ordovician) and fourteen zircons aged 280–245 Ma (Permian to Lower Triassic), all magmatic. There are two small populations aged ~2.6 to 2.8 Ga (Archean, three zircons) and 2.0–1.8 Ga (Paleoproterozoic, four grains). One grain yielded 400 Ma, with very high Th/U ratio (3.41), but this analysis is discordant on a Concordia diagram.

Backscattered electron images of zircon crystals (Figs. 4a-h) show size variations from 10 to 200 μm. Some crystals are rounded to sub-rounded, none shows oscillatory zonation but many have irregular shapes. In general, the elongated crystals with predominantly euhedral, pyramidal terminations, have Permian ages (Figs. 4b, 4h). Some zircon grains display oscillatory zonation, therefore rim and core analyses were undertaken on 10 grains; five of these had similar ages, whereas three recorded early Cambrian to latest

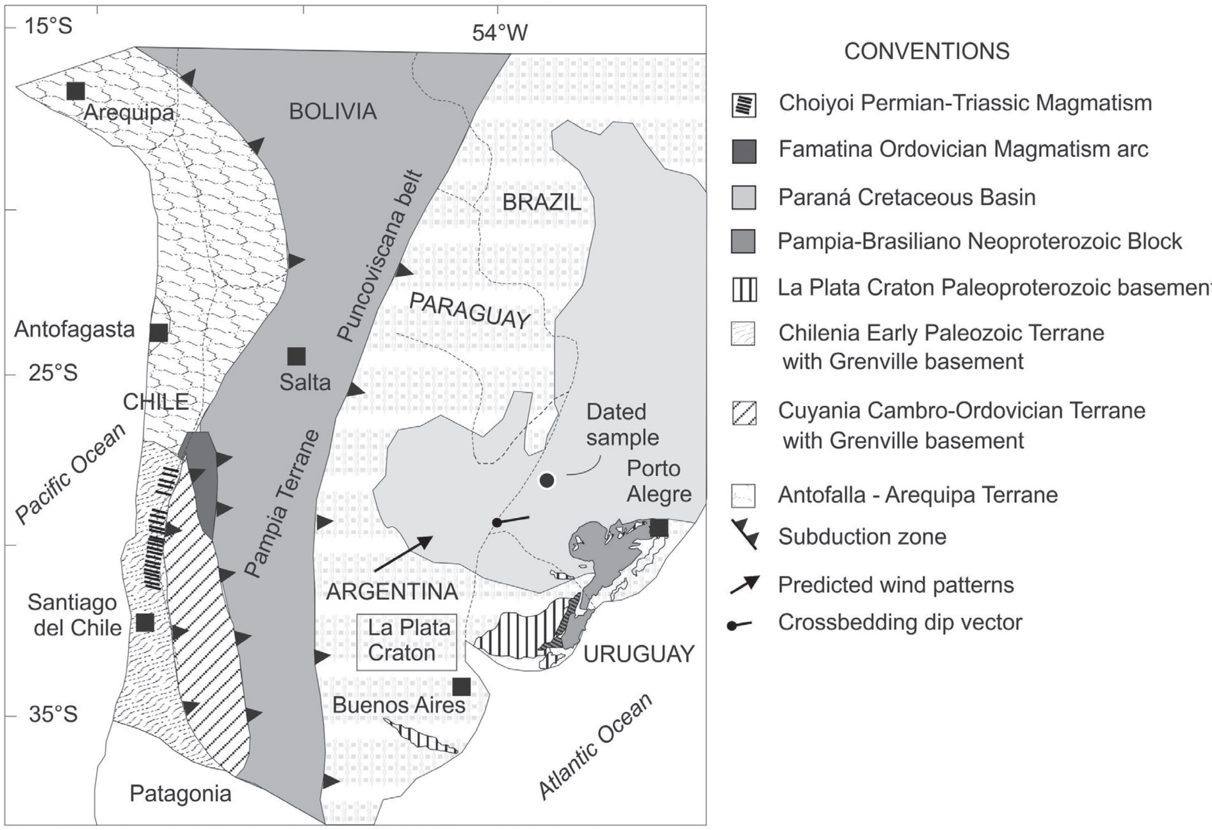

Figure 2 - Geological map of part of South America based on Ramos (2000), Silva et al. (2005), Hartmann et al. (2008), Santos et al. (2002). The map includes wind patterns (Moore et al. 1992) and crossbedding dip vector (Scherer and Goldberg 2007).

Neoproterozoic rims with Mesoproterozoic cores (Fig. 4b) and two had early Neoproterozoic cores.

The U contents of the studied zircons range between 88 and 1078 ppm and many lie between 200 and 400 ppm. Th/U ratios of zircons range between 0.03 and 3.41. Only two analyses resulted in Th/U ratios <0.1 and these have ages of 560 and 631 Ma. These low Th/U spots are typical of metamorphic zircon compositions (e.g. Hartmann et al. 2000). On the other hand, the majority of the ratios are >0.10, common in magmatic zircon. According to Hartmann and Santos (2004), the low Th/U ratio of metamorphic zircon is due to high U, which causes higher metamictization and faster comminution of the grains, transported and deposited in finer grained rocks such as mudstones. Detrital zircon in sandstones such as the studied sample is a record of magmatic events in the source terrane.

DISCUSSION

We consider the dated sandstone layer as an extrudite that originated by sand injection from the underlying (800-m deep) paleoerg. Nevertheless, the sand present in the paleoerg needs a provenance evaluation. The direction of sediment transport in aeolian sandstones of the Botucatu Formation (Early Cretaceous of the Paraná Basin) has been interpreted on the basis of cross-strata dip directions. These indicated palaeowind directions and allowed the reconstruction of regional wind patterns in Midwestern Gondwana (Scherer and Goldberg 2007). Due to the reduced thickness of the Botucatu Formation in the outcrop area, in this work, cross-strata dip directions were compiled from data available in the literature, such as the work of Bigarella and Salamuni (1961), Scherer and Goldberg (2007), and predicted wind patterns

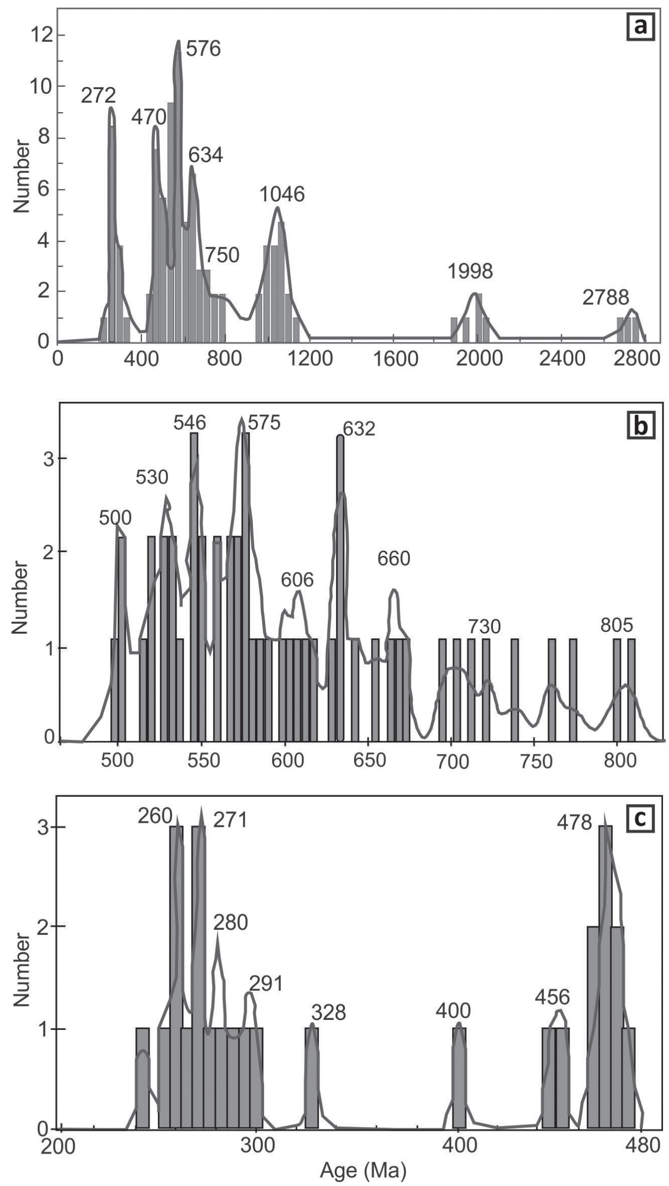

Figure 3 - Frequency histograms and probability curves of zircon U-Pb ages, sample VIS1/2 (sandstone). Main age peaks are indicated. **a)** All ages, from Neoarchean to Lower Triassic; **b)** Neoproterozoic and Cambrian ages (Brasiliano Orogenic Cycle sources); **c)** Post-Cambrian ages dominated by Ordovician (Famatinian sources from the SW) and Permian (Choiyoy sources from SW) ages.

from Moore et al. (1992). Mean vectors were plotted on the map with the "tadpole" symbol and the large arrows show the predicted wind patterns close to the studied area (Fig. 2). In these studies, measurements of cross-strata dip directions in area close to the sample show an average dip direction varying between ~040° to 100°, indicating that the direction of sediment transport was from southwestern to western (SW/W).

Two remarkable results of the age study of detrital zircons from the sandstone layer on top of a basalt flow are the absence of ages younger than

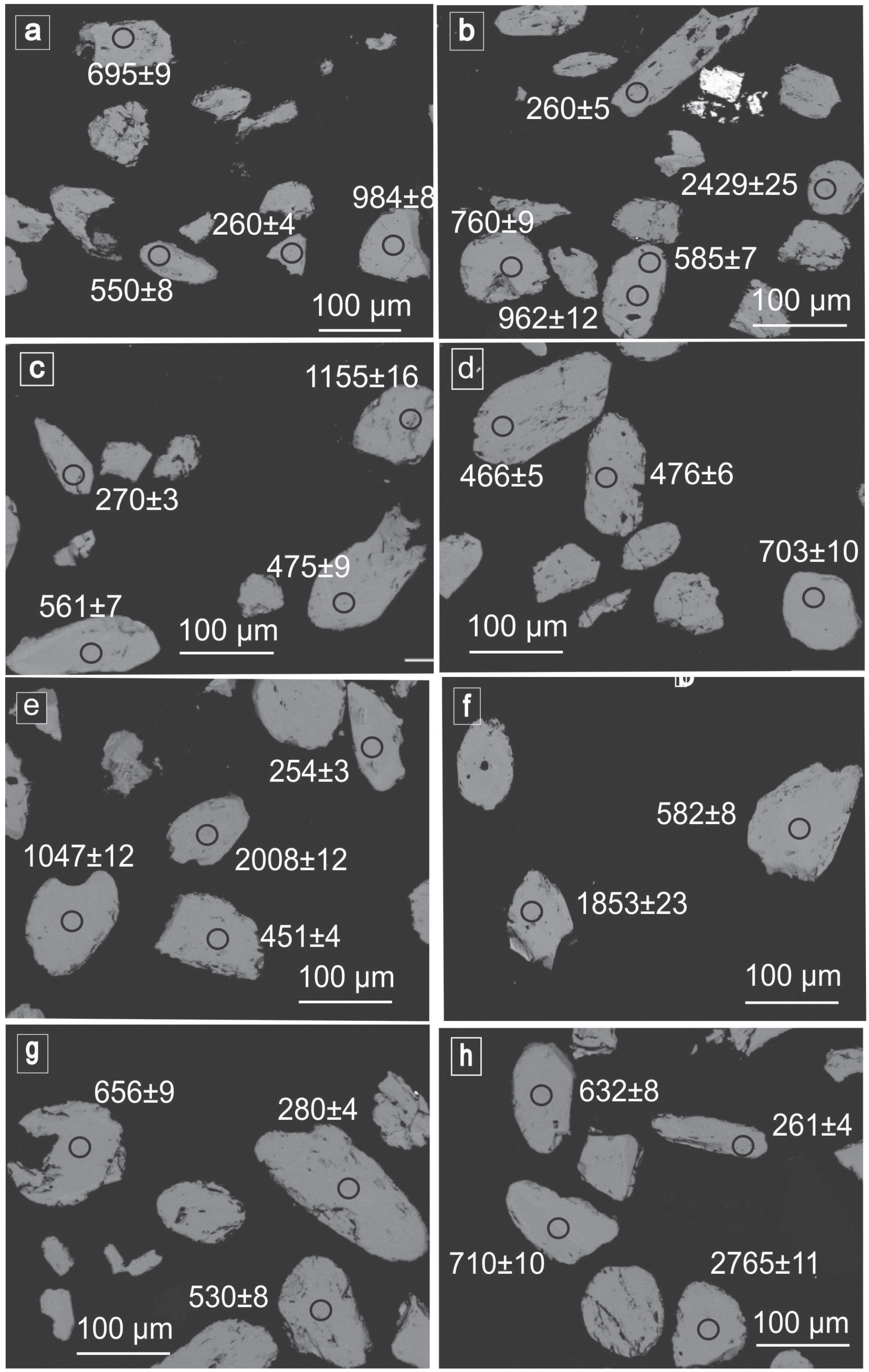

Figure 4 - Backscattered electron images of analyzed zircons, sandstone sample VIS-1/2. Circles indicate position of SHRIMP analyses; U-Pb ages in Ma.

the Permian to Lower Triassic and the presence of the full spectrum of ages from the southern Brazilian Shield and Argentina. No zircons derived from the Serra Geral Group were recognized, even though an 800 m-section of basalts and rhyodacites underlies the sandstone. The volcanic group did not contribute to the sedimentary budget of the deposited sandstone. A quartz sandstone is not expected to form by desert wind activity in a basin on top of basalts. Just as unlikely is a process of wind blowing sand 800 m up the plateau from the underlying Botucatu Formation.

In southernmost Brazil, zircon grains from tonsteins intercalated in Permian sedimentary rocks of the Irati and Rio Bonito Formations (Paraná Basin) yielded SHRIMP ages ~290 Ma (Guerra-Sommer et al. 2008). These zircon crystals probably originated in an active and widespread Lower Permian explosive volcanic event in western Gondwana, which is interpreted as the same volcanism that produced the Choiyoi Group in western Argentina. This event is similar to the October 2011 ash-fall that covered southern Brazil after the Puyehue-Cordón Caulle volcano explosion in Chile.

The southern Brazilian Shield is composed of Archean to Paleoproterozoic rocks from the Rio de La Plata craton, but the Neoproterozoic to Cambrian rocks of the Brasiliano Cycle are voluminous.

La Plata Craton

The ages of Neoarchean (2.66 to 2.77 Ga) and Paleoproterozoic (1.8-2 Ga) are the minor source in the provenance terranes in this study. The Neoarchean ages occur in detrital zircon in the Brazilian Shield (Hartmann et al. 2008) and in detrital zircons from Punta Mogotes Formation, Mar del Plata terrane, Argentina (Rapela et al. 2011). Trans-Amazonian ages are common in Brazil, Uruguay and Argentina (e.g. Santos et al. 2002, Rapela et al. 2011). There is no register in the sample of Trans-Amazonian ages (~2.05 to 2.3 Ga) that would be typical of the Tandilla belt (Argentina) and the Piedras Altas terrane (Uruguay) (Santos et al. 2002), to the south of the studied area. The few detrital zircons from the Paleoproterozoic indicate that the Trans-Amazonian block was little exposed when the Paraná Basin was deposited. Because the Paleoproterozoic crust was intensely reworked in the Brasiliano orogenic Cycle, only a small volume is now exposed.

Mesoproterozoic Ages

Mesoproteozoic ages have been recorded at various locations along the Andean margin (Sunsás Orogeny). Among these, rocks from the Arequipa-Antofalla terrane (e.g. Bahlurg and Hervé 1997), Cuyania terrane (Ramos 2004), Western Sierras Pampeanas (Casquet et al. 2006, Chernicoff et al. 2012) and the Puncoviscana belt (e.g. Escayola et al. 2007) have late and early Mesoproterozoic ages and are interpreted as part of an autochthonous terrane (Schwartz and Gromet 2004).

In Brazil and Uruguay there is little evidence of Mesoproterozoic ages, e.g. Capivarita anorthosite (Chemale et al. 2011) and Sarandi del Y Lineament and Sierra Ballena shear zone (Santos et al. 2002).

Neoproterozoic to Cambrian Ages

Few ages lie between 0.8 and 0.7 Ga; the main concentration is from 660 to 560 Ma and another from 550 to 500 Ma, with highest age peaks at 632, 575 and 546 Ma. These ages are concordant with the geochronological subdivision of the Brasiliano/Pan-African systems of orogens by Silva et al. (2005) into three systems. The BRASILIANO I had collisional climaxes at ca. ~790 and 730-700 Ma, recognized in the southwestern domain of the state of Rio Grande do Sul in the São Gabriel terrane (Chemale 2000) (São Gabriel Orogeny, sensu Hartmann et al. 2000) and Embu Terrane (sensu Campos Neto 2000, Cordani et al. 2002) (see Figs. 1, 2 and 3 in Silva et al. 2005). The BRASILIANO II had collisional climaxes at ca. 640-620 Ma and ca. 600 Ma, represented by three orogens, extending from close to Montevideo city, Uruguay, to northeast of São Paulo city, Brazil, designated from south to north as the Pelotas/Dom Feliciano, Rio Piên and Ribeira Belt. The BRASILIANO III climaxed at ~595-560 and 530-500 Ma, with the Araçuaí orogen and Búzios orogen, respectively. They have counterparts presenting similar paroxysmal timing in the adjacent western Tocantins Province (southern Brasilia Belt) and in the Pan-African orogens as observed by Silva et al. (2005). The temporally equivalent Pan-African orogenic stages from Caby (1998) are, respectively, the Early Pan-African (climax at ca. 800-650 Ma), the Main Pan-African 'Episode' (climax at ca. 650-590 Ma) and the Late Pan-African orogeny with climax at ca. 590-540 Ma.

Some evidence was obtained for juvenile Early Neoproterozoic magmatism by Chernicoff et al. (2011, 2012) from Hf isotope determinations in the Pampia terrane (Puncoviscana metasedimentary rocks, Argentina). SHRIMP U-Pb detrital zircon data from Negro Peinado Formation (ca. 732 ± 29 Ma) and Achavil Formation (791 ± 29 Ma) from metasedimentary rocks of the Famatina belt (see Collo et al. 2009) are related to Brasiliano I/Early Pan-African. Additional orogenic activity in the Pampia terrane indicates the presence of a vast single Brasiliano/Pan-African-Pampean magmatic arc. Schwartz and Gromet (2004), analyzing detrital zircons in Sierras de Córdoba, for example, indicated a population between ~600 to 700 Ma, representative of Brasiliano II and Main Pan-African orogenic cycle. Late Neoproterozoic to Cambrian ages are widespread in the Pampia terrane as magmatic and metamorphic ages; e.g. Schwartz et al. (2008), Chernicoff et al. (2012), Collo et al. (2009), and, Lork et al. (1989). Metamorphic peaks in the Brasiliano/Pan-African cycles (Silva et al. 2005) are five: 840-800 Ma; 730-700 Ma; 640-620 Ma; 590-560 Ma; 520-500 Ma. Four of these peaks correlate with this investigation in Iraí zircons, except for the early Neoproterozic ages.

Based on our U-Pb SHRIMP results, we are encouraged to correlate the Pampia orogen with the Brasiliano/Pan-African cycles as a single magmatic arc, supporting the proposition of Chernicoff et al. (2012).

Ordovician Magmatism

In northwestern Argentina, the Early Cambrian Pampean orogenic belt lies to the west of the Rio de La Plata craton, and was partially overprinted by the Early to Mid-Ordovician Famatinian magmatic arc (Pankhurst et al. 1998, 2006), with intensive deformation in the Late Ordovician. The Famatinian belt (Fig. 2) has been considered as a continental marginal arc related to subduction during the approach and collision of the Precordillera terrane (Pankhurst et al. 2006). The Famatina magmatic arc was formed in a relatively restricted time span around 480 – 470 Ma (Ramos 2000).

The late middle to late Ordovician ages (~465-450 Ma) are compatible with the Cuyania block. This block is considered to have detached from Laurentia and moved towards Gondwana in the Middle to Late Ordovician times, and the time of collision is tracked by the cessation of arc-related magmatic activity in the Gondwana protomargin at about 465 Ma in western Sierras Pampeanas. Ages around 454 Ma correspond to syncollisional and postcollisional magmatism (Ramos 2004).

Permian Magmatism

The Permian magmatism corresponds to the Choiyoi volcanic rocks of rhyolitic and dacitic composition associated with shallow level plutons of similar composition (e.g. Mpodozis et al. 1976). Our geochronologic data show that Permian magmatism is very extensive in time and space, concordant with observations made in La Pampa province and North Patagonian Massif (Pankhurst et al. 2006). The oldest age is 295 ± 5 Ma and the youngest is 244 ± 6 Ma (Lower Triassic).

Pankhurst et al. (2006) attributed the more voluminous and widespread nature of this magmatism to major access of heat to the crust following break-off of the subducted slab after a continental collision that was initiated in Carboniferous times.

CONCLUSIONS

The absence of wind-blown, high-angle stratification in the sand extrudite and the absence of detrital zircon ages younger than the Permian that would have originated in the 800 m-thick basalt-rhyodacite sequence, makes it very unlikely that the quartz sand deposited in a paleoerg dune. Sand injection from the underlying Botucatu Formation paleoerg is the preferred interpretation.

Our data corroborate the measured direction of sediment transport in aeolian sandstones of the Botucatu Formation (Early Cretaceous of the Paraná Basin) based on cross-strata dip directions. These indicate palaeowind directions from southwest to west (SW/W). These particularly explain the robust presence of Mesoproterozoic, Permian and Ordovician magmatic populations. There is no register in the detrital zircons of Trans-Amazonian ages (~2.05 to 2.3 Ga) typical of the Tandilla belt (Argentina) and Piedras Altas terrane (Uruguay), corroborating this premise.

1. The Neoproterozoic to Early Cambrian ages suggest an uninterrupted development of arc magmatism on the Pampia terrane from Brasiliano-Pan-African to Pampean times (applying the proposed model of Chernicoff et al. 2012), as indicated by the occurrence of numerous zircon ages of detrital, magmatic and metamorphic ages.
2. The few zircons from Neo-Archean and Paleoproterozoic terranes indicate that the Trans-Amazonian block was poorly exposed when the Botucatu Formation paleoerg was deposited. The Paleoproterozoic crust was intensely reworked in Brasiliano orogenic times.
3. The Permian ages are similar to the ages obtained on zircons from tonsteins in the Paraná Basin, which originated from ash-fall deposits from intense volcanism in Argentina.

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RESUMO

A determinação de idade, com microssonda iônica, de 102 cristais detríticos de zircão de um extrudito de areia, província vulcânica Paraná, estabelece limites sobre a origem das numerosas camadas de areia presentes nesta grande província de derrames basálticos. As idades U-Pb em zircão refletem quatro principais ciclos orogênicos: Mesoproterozóico (1155-962 Ma), final do Neoproterozóico ao início do Cambriano (808-500 Ma) e dois Paleozóicos (Ordoviciano – 480 450 Ma, e Permiano a Triássico Inferior – 296 a 250 Ma). Duas outras pequenas concentrações estão presentes no Neoarqueano (2,8 a 2,6 Ga) e Paleoproterozóico (2,0-1,7 Ga). Picos de idades de zircão coincidem com os pulsos de vários eventos ígneos no Escudo Brasileiro pré-cambriano e orogenia ativa na Argentina. Uma importante delimitação da origem da areia é a ausência de idades de zircão proveniente dos basaltos cretáceos subjacentes, apoiando assim uma origem de injeção da areia como um extrudito que emanou do paleoerg que constitui a Formação Botucatu.

Palavras-chave: Formação Botucatu, Brasil, idades Neoarqueanas a Paleozóicas, proveniências, extrudito de areia, idades U-Pb de Zircão.

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SUPPLEMENTARY MATERIAL

TABLE SI - U-Pb SHRIMP isotopic data from detrital zircons of the studied sand extrudite, sample VIS-1/2, C-D populations; c = core, r = rim.