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Hf isotope study of Palaeozoic metaigneous rocks of La pampa province and implications for the occurrence of juvenile early Neoproterozoic (Tonian) magmatism in south-central Argentina

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ABSTRACT

On a global scale, juvenile Tonian (Early Neoproterozoic) magmatic rocks are associated with the extensional events that lead to the breakup of the Rodinia supercontinent. In Argentina, no geological record is available for this time interval, lasting from 1000 to 850 Ma. We present indirect evidence for the existence of Tonian extension in Argentina, as supported by Hf and Nd isotope determinations on Phanerozoic magmatic and sedimentary rocks. We mainly focus on our own Hf isotope determinations carried out on U–Pb SHRIMP dated zircons from Palaeozoic metaigneous rocks of La Pampa province, south-central Argentina, i.e. metagabbros of Valle Daza, dioritic orthogneiss of Estancia Lote 8, and metadiorite of Estancia El Carancho, having found that these rocks were derived from sources of ca. 920 to ca 880 Ma, with ϵHf values between +6.83 and + 9.59. Inherited zircons of this age and character identified in these rocks also point to the same source. We also compile additional Hf and Nd studies from previous work on Phanerozoic magmatic and sedimentary rocks. We preliminarily compare the age of the juvenile Tonian sources referred to in our work with that of two extensional events identified in the São Francisco craton, Brazil.

1. Introduction

No geological record is available in Argentina for the time interval lasting from 1000 to 850 Ma, i.e. Tonian (Early Neoproterozoic), a period also not extensively represented within Rodinia. Ca. 870–850 bimodal intrusions (e.g. in South China, Africa, Scandinavian Caledonides, Scottish promontory of Laurentia, etc.) have been interpreted to represent the first signs of a superplume event, followed by continental rifting and breakup (Li et al., 2008, and references therein). The latter authors envisage a mechanism for the formation of the Rodinia superplume that comprises mantle avalanches surrounding the supercontinent, possibly enhanced by the thermal insulation effect of the supercontinent.

In the Upper Tonian period, the Macaúbas rift system generated in the São Francisco/Congo continent—envisaged to represent the precursor stage of the Araçuaí orogen—reached its full development, and is represented by bimodal magmatism; the earlier stage (Early Tonian) of the this magmatism is mostly preserved in the West Congo counterpart of the Araçuai orogen (e.g. Soares et al., 2008, and references therein).

In this work we present indirect evidence for the existence of Tonian extension in Argentina, as supported by Hf and Nd isotope determinations on Phanerozoic magmatic and sedimentary rocks. We focus particularly on our own Hf isotope determinations carried out on U–Pb SHRIMP dated zircons from Palaeozoic metaigneous rocks in La Pampa province (metagabbros of Valle Daza, dioritic orthogneiss of Estancia Lote 8, metadiorite of Estancia El Carancho) (Fig. 1).

Additional indirect evidence is given by Nd isotope data of Phanerozoic magmatic units outside our study area, i.e. syenite-carbonatite of Sierra de Maz (Casquet et al., 2008), granodiorites Serrucho and Platero of western North-Patagonian region (Pankhurst et al., 2006), and Mafic Unit of the Illapel Igneous

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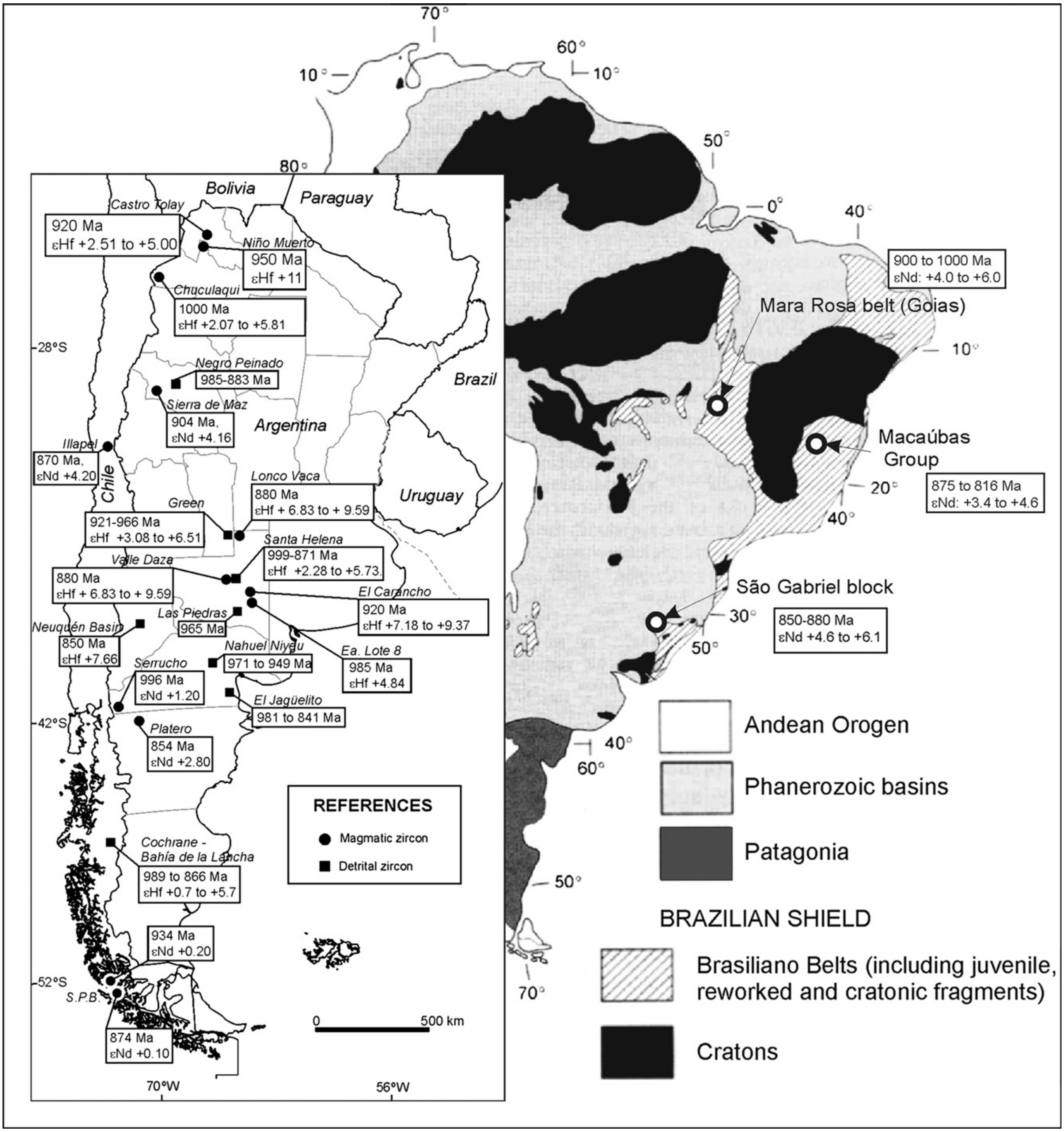

Fig. 1. Locality map of magmatic rocks derived from juvenile Tonian sources in Argentina (left), and juvenile Tonian rocks exposed in the Brazilian shield (right). S.P.B.: South Patagonian Batolith.

Complex, central Chile (Morata et al., 2010), all of them derived from juvenile Tonian sources (Fig. 1). See Table 1 for easy reference.

For the sake of comparison, mention is also made of the closest exposed juvenile Tonian magmatic units outside Argentina, i.e. the rift-related ca. 875 Ma plutonic suite associated with the precursor basin of the Araçuaí orogen, eastern Brazil (Salto da Divisa Formation, e.g. Soares et al., 2008), and the ca. 880 Ma meta-mafic rocks of the São Gabriel Block, southernmost Brazil (e.g. Saalmann et al., 2005).

Furthermore, based on the occurrence of juvenile Tonian detrital zircon populations, we discuss the time intervals in which rock units of this age and character may have been exposed, so as to have been one of the sources for, e.g. Neoproterozoic and Cambrian metasedimentary rocks in La Pampa province (Santa Helena Schist and Green Schist, respectively), Neopaleozoic sedimentary rocks in southwestern Patagonia (Cochrane Unit — Bahía de la Lancha Formation) and Cretaceous sedimentary rocks in the Neuquén basin (Rayoso and Candeleros Formations).

Finally, we speculate on whether some of the Tonian detrital zircon grains recovered from other Phanerozoic basins, but still lacking Hf isotope determinations, may be juvenile, focussing on two Lower Palaeozoic units (Negro Peinado and Las Piedras Formations, exposed in La Rioja and La Pampa provinces, respectively).

Table 1
Selected isotopic data of magmatic rocks derived from juvenile Tonian sources (see Fig. 1 for location).

Magmatic rock type, and location	T_{DM} (Hf) (Ma)	ϵ_{Hf} values	T_{DM} (Nd) (Ma)	ϵ_{Nd} values	U–Pb shrimp age of inheritance (Ma)	ϵ_{Hf} values of inheritance	Reference
Metagabbro Valle Daza, La Pampa	880 (830–1000)	+6.83 to +9.59					This paper
Dioritic orthogneiss Ea. Lote 8, La Pampa					985	+ 4.84	This paper
Metadiorite El Carancho, La Pampa	920	+7.18 to + 9.37					Chernicoff et al. (2009b and 2011)
Diorite Castro Tolay, Puna	920	+2.51 to +5.00					Zappettini and Santos (2011)
Granodiorite Chuculaqui, Puna	1000	+2,07 to +5.81					Quenardelle et al. (2010; personal communication)
Dacite El Niño Muerto, Puna					950	+11	Matteini et al. (2008)
Syenite–carbonatite Sierra de Maz, La Rioja			904	+4.16			Casquet et al. (2008)
Mafic Unit of Illapel Igneous Complex, central Chile			870	+4.2			Morata et al. (2010)
Granodiorite Serrucho, Chubut			996	+1.2			Pankhurst et al. (2006)
Granodiorite Platero, Chubut			854	+2.8			Pankhurst et al. (2006)
Granodiorite (sample SI9928) of South Patagonian Batolith, SW Chile			934	+0.2			Hervé et al. (2007)
Granodiorite (sample FO0211) of South Patagonian Batolith, SW Chile			874	+0.1			Hervé et al. (2007)

2. Evidence from metaigneous rocks in La Pampa

2.1. Valle Daza metagabbro

2.1.1. Hf isotope determinations: methodology

Hf-isotope analyses were carried out using a New Wave/Merchantek UP213 laser-ablation microprobe, attached to a Nu Plasma multi-collector ICP-MS at GEMOC (Geochemical Evolution and Metallogeny of Continents), Macquarie University, Sydney. Operating conditions include a beam diameter of ~55 μm, a 5 Hz repetition rate, with energy of ~0.4–0.8 mJ. Typical ablation times were 100–120 s, resulting in pits 40–60 μm deep. Mud Tank (MT) zircon was used as reference material which has an average $^{176}Lu/^{177}Hf$ ratio of 0.282522 ± 42 (2SE) (Griffin et al., 2007). MT analyzed in this study was within reported range (0.282514 ± 26; $n = 2$). More detail of the analytical techniques, precision and accuracy is described by Griffin et al. (2000, 2004).

Initial $^{176}Hf/^{177}Hf$ ratios are calculated using measured $^{176}Lu/^{177}Hf$ ratios, with a typical 2 standard error uncertainty on a single analysis of $^{176}Lu/^{177}Hf$ ± 1–2%. Such error reflects both analytical uncertainties and intragrain variation of Lu/Hf typically observed in zircons. Chondritic values of Scherer et al. (2001) (1.865×10^{-11}) have been used for the calculation of ϵ_{Hf} values. Whilst a model of $(^{176}Hf/^{177}Hf)_i = 0.279718$ at 4.56 Ga and $^{176}Lu/^{177}Hf = 0.0384$ has been used to calculate model ages (T_{DM}) based on a depleted mantle source, producing a present-day value of $^{176}Hf/^{177}Hf$ (0.28325) (Griffin et al., 2000, 2004). T_{DM} ages, which are calculated using measured $^{176}Hf/^{177}Hf$ of the zircon, give only the minimum age for the source material from which the zircon crystallized. We have therefore also calculated a "crustal" model age (T^{C}_{DM}) for each zircon which assumes that the parental magma was produced from an average continental crust ($^{176}Lu/^{177}Hf = 0.015$) that was originally derived from depleted mantle.

2.1.2. Results

The Famatinian metagabbro (zircon U–Pb SHRIMP dating ca. 450 Ma; Chernicoff et al., 2008b) scarcely exposed at Valle Daza and Sierra de Lonco Vaca, La Pampa province (Fig. 1), represents the southern continuation of the Ordovician back-arc magmatism corresponding to the mafic-ultramafic rocks of the Sierra de San Luis (Chernicoff et al., 2005, 2009a; Zappettini et al., 2005). This back-arc metagabbro is located about 50 km to the east of the southern segment of the Famatinian magmatic arc, in the province of La Pampa (Chernicoff et al., 2010a).

The type area of the Valle Daza metagabbros is located 4 km south of the Valle Daza estate at the southern shore of the Valle Daza salt pan (37°04′S–65°30′W). At this site, the metagabbros, mostly covered by Quaternary sediments, exhibit a conspicuous NNE trending foliation. At Lonco Vaca, a quarry (35° 07′S–65° 04′W) helps with the identification of the individual lenses of metagabbro, hosted by Cambrian micaschists and paragneisses pertaining to the Green Schist (Chernicoff et al., 2007).

In this section we present the results of the Hf isotope determinations of the dated zircon crystals of sample VD1 (zircon U–Pb SHRIMP ages, after Chernicoff et al., 2008b). The model ages (T_{DM}) yielded 880 Ma (range 830–1000 Ma), whereas ϵ_{Hf} values range from +6.83 to +9.59 (Fig. 2). The latter values, in conjunction with the relatively low $^{176}Lu/^{177}Hf$ ratios, may indicate that the juvenile Tonian source from which the zircons crystallized possibly had a minor contamination with older crust, and/or was derived from weakly depleted mantle (cf. Chen et al., 2007) (Table 2; Fig. 2). The lack of correlation between the $^{176}Lu/^{177}Hf$ ratios and the ϵ_{Hf} values of the dated zircons of sample VD1 does not support any evidence of crustal contamination (which would be expected if there was a positive correlation; cf. Vervoort and Blichert-Toft, 1999).

2.2. Dioritic orthogneiss of Estancia Lote 8

2.2.1. Zircon U–Pb SHIMP dating: methodology

Sample MG94b (dioritic orthogneiss) was crushed, milled, sieved at 60 Mesh, and washed to remove the clay and silt fractions. The remaining material, corresponding to fine sand and very fine sand, was dried and processed by two heavy liquids: LST (lithium–sodium tungstate, density 2.8) and TBE (tetra-bromo-ethane, density 3). The heavy mineral concentrates were separated into four fractions using a Frantz® magnetic separator. Zircon grains were picked from the less magnetic fraction at 1 A and 5° inclination and then mounted in an epoxy disc of 2.5 cm diameter together with the analytical standards. The mount was polished and coated with carbon for imaging using a JEOL6400 Scanning Electron Microscope at the Centre for Microscopy, Characterization and Microanalyses of the University of Western Australia. This

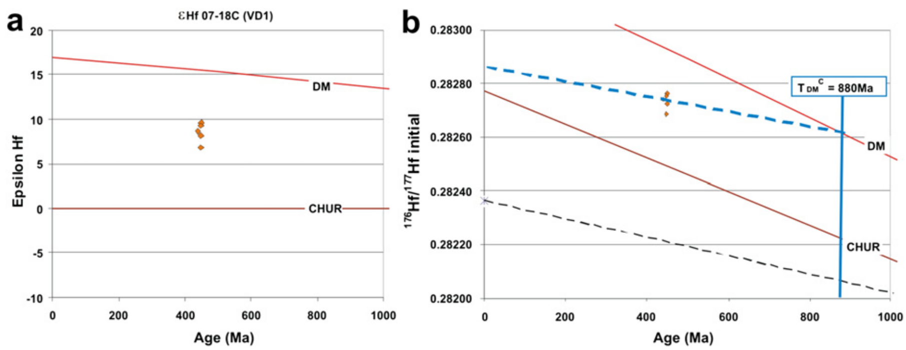

Fig. 2. a) Plot of ϵHf values versus ages of the dated zircons of sample VD1, b) plot of $^{176}Hf/^{177}Hf$ ratios versus ages of the dated zircons of sample VD1. The Depleted Mantle model age (crustal) is Early Neoproterozoic (Tonian; 880 Ma). DM: Depleted Mantle; CHUR: Chondritic Uniform Reservoir. Zircon U–Pb SHRIMP dating of sample VD1, after Chernicoff et al. (2008b).

carbon coating was removed and replaced for a gold coating for SHRIMP U–Pb analyses.

Sensitive High Mass Resolution Ion MicroProbe (SHRIMP II) U–Pb analyses were performed at Curtin University of Technology using an analytical spot size of about 20–25 μm. Individual analyses are composed of nine measurements repeated in five scans. The following masses were analyzed for zircon: (Zr_2O, ^{204}Pb, background, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{238}U, ^{248}ThO, ^{254}UO). The standards D23 and NBS611 were used to identify the position of the peak of the mass ^{204}Pb, whereas the calibration of the U content and the Pb/U ratio were done using the zircon standard BR266 (559 Ma, 903 ppm U). Data were reduced using the SQUID© 1.03 software (Ludwig, 2001) and the ages calculated using Isoplot© 3.0 (Ludwig, 2003). The presented Silurian age is mean average $^{206}Pb/^{238}U$ age calculated at 2σ level.

2.2.2. Results

U–Pb SHRIMP data for a dioritic orthogneiss (sample MG94b) exposed at the Estancia Lote 8 (37° 48.075′ S–64° 46.041′ W, La Pampa; Fig. 1) have yielded 432.3 ± 3.5 Ma (Lower Silurian, Telychian); concordia age is given in Fig. 3a (not published previously). This orthogneiss is coeval with the nearby Andersen Granodiorite dated at 431 ± 12 Ma (U–Pb in zircon, Tickyj et al., 1999), both being intruded in the southernmost portion of the Rio de la Plata craton (Zappettini et al., 2010). Both granitoids are possibly post-tectonic.

Amongst the inherited magmatic (Th/U: 0.27) zircons, the oldest is Tonian (985.5 Ma) and juvenile ($\epsilon_{Hf} = +4.84$), which is herein interpreted as a sign for the existence of host rocks of this age and character at the present location; other inherited zircons in this unit are Late Neoproterozoic to Early Palaeozoic (Fig. 3).

2.3. El Carancho metadiorite

Evidence for the occurrence of the Pampean magmatic arc at Estancia El Carancho, La Pampa province (37°34`S–65°11′W; Fig. 1) has recently been published by Chernicoff et al. (2009b, 2011). These authors provide both zircon U–Pb SHRIMP dating and Hf isotope determinations for an arc-type metadiorite (sample MG91b). SHRIMP dating of this sample yielded 520.0 ± 5.2 Ma—MSWD = 1.7; 2σ—(Lower Cambrian).

Hafnium model ages of the dated zircons yielded 920 Ma, with ϵ_{Hf} values between +7.18 and +9.37. These results have been interpreted to indicate that the Lower Cambrian El Carancho metadiorite was derived from a juvenile Tonian source.

3. Evidence from other magmatic units

In this section we compile additional indirect evidence for juvenile Tonian derivation of some Phanerozoic magmatic units outside La Pampa province, based on whole-rock Nd isotope determinations, and a smaller number of Hf isotope determinations on dated zircons.

3.1. Castro Tolay dioritic stock

A dioritic stock exposed at the southwestern part of the Sierra de Tusaquillas, Jujuy (Fig. 1), with an anorogenic signature assigned to a back-arc to intracontinental rift setting, yielded a zircon U–Pb SHRIMP age of 154.2 ± 0.92 Ma (Zappettini, 2008). Zappettini and Santos (2011) have recently carried out Hf isotope determinations in the dated zircons, obtaining a consistent T_{DM} (Hf) = 920 Ma with ϵ_{Hf} values between +2.51 and +5.00, which the authors attribute to a juvenile Tonian source from which the magma was derived.

3.2. Chuculaqui granodiorite

Quenardelle et al. (2010) have recently reported an Olenekian age (246.5 ± 2.4 Ma U–Pb SHRIMP in zircons) for the metaluminous granodiorite of Chuculaqui (west of the Arizaro salt lake, Salta province), which pertains to a calc-alkaline orogenic suite representing the northernmost Gondwanan magmatism in Argentina.

Table 2
Hf isotopic data of five dated zircons of sample VD1, Valle Daza metagabbro.

Spot	Age[a] Ma	($^{176}Hf/^{177}Hf$) error 1σ	($^{176}Lu/^{177}Hf$)	($^{176}Yb/^{177}Hf$)	($^{176}Hf/^{177}Hf$)	(epsilon/Hf) error 1σ	T (DM) (Ma)	T(DM) crustal	Hf Chur (t)	Hf DM (t)
c.1-1	439.3	0.282746 ± 0.000015	0.000519	0.02234	0.282742	8.60 ± 0.52	710	880	0.282499	0.282935
c.1-2	447.6	0.282692 ± 0.000013	0.000655	0.02900	0.282687	6.83 ± 0.45	790	1000	0.282494	0.282929
c.2-2	449.9	0.282766 ± 0.000013	0.000347	0.01489	0.282763	9.59 ± 0.45	680	830	0.282492	0.282927
c.2-4	448.2	0.282758 ± 0.000010	0.000569	0.02103	0.282753	9.20 ± 0.35	690	850	0.282493	0.282929
c.5-1	448.9	0.282727 ± 0.000009	0.000402	0.01513	0.282724	8.17 ± 0.32	730	920	0.282493	0.282928

Note: ^{176}Lu decay constant = 1.865×10^{-11} (Scherer et al., 2001).
[a] Age U–Pb SHRIMP (after Chernicoff et al., 2008b).

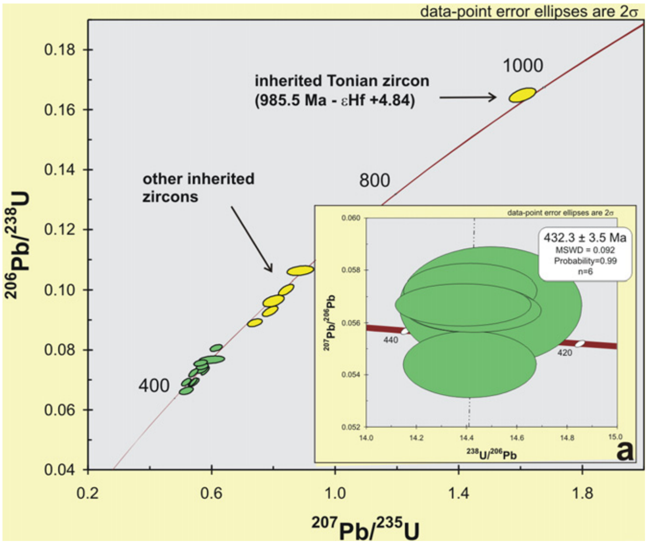

Fig. 3. Concordia diagram for all zircon fractions from the Dioritic Orthogneiss Estancia Lote 8 (sample MG94b); inherited (Tonian and others) zircons shown as yellow coloured ellipses. Inset (a): Inverse concordia plot ($^{207}Pb/^{206}Pb$ versus $^{238}U/^{206}Pb$) of Silurian zircons (green coloured ellipses) providing a crystallization age of 432.3 ± 3.5 Ma (MSWD = 0.092; 2σ). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Hf isotope determinations in the dated zircons provided by these authors (personal communication) indicate a model age (T_{DM}) = 1000 Ma with ϵ_{Hf} values between +2.07 and +5.81. Hf data indicates that the unexposed crustal source of the granodiorite corresponds to juvenile magmatic rocks of Tonian age.

3.3. El Niño Muerto dacite

The El Niño Muerto Dacite is exposed in the Puna plateau and is part of the Famatinian magmatism of the Faja Eruptiva Oriental (Hauser et al., 2010).

Zircon LA-ICPMS U–Pb dating carried out by Hauser et al. (2010) yielded a crystallization age of ca. 495 Ma (Upper Cambrian). The same authors report whole-rock Nd isotope determinations on the dacite yielding ϵ_{Nd} values between −9.7 and −5.9, and T_{DM} (Nd) between 1620 and 1790 Ma. However, Hf isotope determinations on the (ca. 495 Ma) dated zircon crystals yielded ϵ_{Hf} values between +1 and +3 (cf. Fig. 3, Matteini et al., 2008), suggesting a juvenile source for the Upper Cambrian magma.

In addition, Matteini et al. (2008) reported the identification of an inherited zircon of Tonian age and distinct juvenile character, i.e. ca. 950 Ma and ϵ_{Hf} +11, which could be interpreted as a indication of the existence of (a component of) juvenile Tonian host rocks at the present location.

3.4. Syenite–carbonatite of sierra de Maz

Casquet et al. (2008) identified and dated deformed syenites–carbonatites in the Sierra de Maz, La Rioja (Fig. 1). Zircon U–Pb SHRIMP dating of these rocks yielded ca 570 Ma. At this reference age, T_{DM} (Nd) average 904 Ma, and ϵ_{Nd} averages +4.16, which the authors attributed to a major contribution from a depleted mantle source. Hence, these data indicate that the alkaline, Ediacaran magmatism of Sierra de Maz must have been derived from a juvenile Tonian source (see Discussion, below).

3.5. Mafic unit of the illapel igneous complex

Zircon LA-ICP-MS U–Pb dating of the Mafic Unit of the Illapel Igneous Complex (Fig. 1) presented by Morata et al. (2010) yielded ca. 118–115 Ma (Cretaceous). These authors also report Nd isotope determinations on gabbros from this Unit, that yield ϵ_{Nd} values of +4.2, and T_{DM} (Nd) = 870 Ma, hence indicating a juvenile Tonian derivation of the Mafic Unit. The reported Nd isotope studies are consistent with the $^{87}Sr/^{86}Sr$ ratios of 0.70335, also given by Morata et al. (2010).

3.6. Granodiorites Serrucho and Platero

Both Serrucho and Platero Granodiorites are exposed in the western North-Patagonian region (Fig. 1). Zircon U–Pb SHRIMP dating of both granodiorites yielded ca. 330 Ma (Pankhurst et al., 2006). These authors also carried out Nd isotope determinations on both granodiorites. Serrucho Granodiorite yielded T_{DM} (Nd) = 996 Ma, and ϵ_{Nd} = +1.2 (consistent with $^{87}Sr/^{86}Sr$ of 0.704625). Platero Granodiorite yielded T_{DM} (Nd) = 854 Ma, and ϵ_{Nd} = +2.8 (consisting with $^{87}Sr/^{86}Sr$ of 0.703373). We consider that these data indicate that these two Neopaleozoic granitoids were derived from a juvenile Tonian crust.

It is interesting to note that Pankhurst et al. (2006) report the zircon U–Pb SHRIMP dating of two other Neopaleozoic granitoids of the same region –Laguna del Toro Granodiorite and Piedra del Aguila Granite (ca. 293 Ma and ca. 290 Ma, respectively)–, where although no Nd isotope determinations were carried out, inherited Tonian zircons of ca. 996 Ma and ca. 882 Ma, respectively, were identiified. The latter inheritance could be interpreted as pointing to a (juvenile?) Tonian component in the country rocks. Notably, such type country rocks may have been exposed during Lower Cambrian times, as indicated by the Tonian detrital zircon populations identified in the El Jagüelito and Nahuel Niyeu Formations (981–841 Ma and 971–949 Ma, respectively) of the North-Patagonian massif (see also Section 5.5, below).

3.7. South Patagonian batolith

Zircon U–Pb SHRIMP dating of the magmatic units of the South Patagonian Batolith in southern Chile (47–53°S), have allowed Hervé et al. (2007) to identify the long life of this batolith, developed from Late Jurassic to the Neogene.

Nd isotope determinations on a granodiorite dated at ca. 122 Ma (Aptian; Cretaceous 3 stage) yielded a moderately positive ϵ_{Nd} value of +0.2, and T_{DM} (Nd) = 934 Ma, suggesting the existence of a juvenile Tonian input in the melt from which this rock crystallized; the juvenile character of the source material is also in agreement with the $^{87}Sr/^{86}Sr$ ratios of 0.704254 reported for this rock.

Nd isotope determinations on another granodiorite, dated at ca. 20 Ma (Neogene stage), yielded a moderately ϵ_{Nd} value of +0.1, and T_{DM} (Nd) = 874 Ma, again suggesting the existence of a juvenile Tonian input in the melt from which this rock crystallized; the juvenile character of the source material is again in agreement with the $^{87}Sr/^{86}Sr$ ratios of 0.704681 reported for this granodiorite.

In addition, Hervé et al. (2007) also identified inheritance at ca 923 Ma in a granite dated at ca 127 Ma (Seno Marsh Granite), and at ca. 985 Ma in a gneiss that has scattered ages between 160 and 985 Ma.

According to Hervé et al. (2007), the later stages of the South Patagonian Batolith resulted from incremental assembly of small plutons generated at greater depths and with higher ϵ_{Nd} values, as opposed to the large crustal magma chambers developed in the early stages (Late Jurassic to Cretaceous 1; associated with lower ϵ_{Nd}

values). The juvenile Tonian inheritance would (partly) reflect the crust type through which the magmas passed at the later stages of the South Patagonian Batolith, this being in agreement with the juvenile Tonian derivation of these magmas.

4. Exposed juvenile Tonian magmatic units

The closest, exposed juvenile Tonian magmatic rocks are located in eastern and southern Brazil, and are briefly referred to below.

4.1. Mara Rosa belt (Goiás)

The Neoproterozoic juvenile Goiás Magmatic Arc (GMA) of Central Brazil is composed of volcano-sedimentary sequences associated with calcic to calc-alkaline tonalite/granodiorite gneisses, the lower part of this arc being the most extensive exposure of Tonian-Early Cryogenian rocks in South America (Pimentel and Fuck, 1992). These units first evolved as intraoceanic island arcs with the crystallization of very primitive tholeiitic to calc-alkaline volcanic rocks and associated tonalites/granodiorites at ca. 890–860 Ma.

The northern exposures of the GMA (ca. 14°S/49°15′W) include the extensional volcano-sedimentary Mara Rosa belt (860 Ma; Pimentel et al., 2000; Junges et al., 2002; Fuck et al., 2006). Zircons from a metavolcanic rock of this unit have recently yielded a U–Pb crystallization age of 916 ± 5 Ma with positive ϵ_{Hf} values (+8 to +12) suggesting that the host magma derived from a depleted mantle (Matteini et al., 2010).

The Western Goias region (ca. 16°S/51°30′W) includes the Matrinxã Gneiss (895Ma, T_{DM} (Nd) 900 Ma, ϵ_{Nd} +6.0, $^{87}Sr/^{86}Sr$ 0.7026; Pimentel and Fuck, 1994) and the Sanclerlândia Gneiss (940 Ma, T_{DM} (Nd) 900 to 1000 Ma, ϵ_{Nd} +4.0/+6.0, $^{87}Sr/^{86}Sr$ 0.7025; Pimentel and Fuck, 1994).

Most of dominantly juvenile Tonian and Early Cryogenian rocks of eastern South America were destroyed/consumed by the successive collisions of the Brasilano orogen during Late Cryogenian and Ediacaran.

4.2. Macaúbas group

The magmatic rocks of the Macaúbas Group, which represent the precursor stage of the (Brasiliano-age) Araçuaí orogen of eastern Brazil (ca. 17°30′S/43°W), comprise (amongst other rock types) an A-type granite-gabbro suite dated at ca. 875 Ma (Salto da Divisa Formation) and ultramafic rocks (ophiolites) of the Riberão da Folha Formation dated at 816 ± 72 Ma (Sm-Nd whole-rock isochron age), with ϵ_{Nd} values ranging from +3.4 to 4.6 (Soares et al., 2008, and references therein). These mostly juvenile Tonian rocks are preserved to the east of the São Francisco craton (yet, most of the Early Tonian rift-related bimodal magmatism is preserved in the West Congo counterpart of the Araçuai orogen; Soares et al., 2008).

4.3. Meta-mafic rocks of the São Gabriel block

In the São Gabriel Block of southernmost Brazil (at ca. 31°S/53°W) there are exposures of mostly juvenile Tonian meta-mafic rocks (Leite et al., 1998). Magnesian schists and serpentinites of the Cerro do Ouro Formation are dated at ca. 880–850 Ma, with T_{DM} (Nd) between 900 and 1350 Ma, and ϵ_{Nd} values between +4.6 and +6.1 (e.g. Saalmann et al., 2005).

5. Timing of the exposure of the juvenile Tonian magmatic units in Argentina

The depositional ages of sedimentary rocks including juvenile Tonian detrital zircon grains give a clue as to when rocks of this age and character were exposed in Argentina. With this premise in mind, we examine available data from Santa Helena Schist, Green Schist, Cochrane Unit—Bahía de la Lancha Formation and two Formations of the Neuquén basin (Table 3).

5.1. Santa Helena Schist

Depositional age of this unit, exposed in La Pampa, is ca. 556 to 530–520 Ma (Zappettini et al., 2010), and the detrital zircon population of interest is dated at 999–871 Ma (zircon U–Pb SHRIMP), with ϵ_{Hf} values between +2.28 and +5.73.

5.2. Green Schist

Chernicoff et al. (2007, 2008a) report a depositional age of 500–465 Ma for these schists that crop out in southern San Luis. The detrital zircon population of interest ranges 921 to 966 Ma (U–Pb SHRIMP), with ϵ_{Hf} values between +3.08 and +6.51 (Chernicoff et al., 2011).

5.3. Cochrane unit — Bahía de la Lancha formation

Both the Cochrane Unit and the Bahía de la Lancha Formation integrate the Eastern Andean Metamorphic Complex, in southwestern Patagonia, of uncertain lower and upper age limits (possibly Carboniferous age, prior to ca. 310 Ma; Fig. 2, in Augustsson et al., 2006).

The detrital zircon population of interest is dated at 989 to 866 Ma (U–Pb SHRIMP), with ϵ_{Hf} values between +0.7 and +5.7 (Augustsson et al., 2006).

5.4. Rayoso and Candeleros formations

Both formations referred to in this section belong to the Cretaceous segment of the Neuquén Basin. The depositional age of the Rayoso Formation is Aptian-Albian (ca.125-ca. 105 Ma), and that of the Candeleros Formation is Early Cenomanian (ca.100–ca.95); e.g. Tunik et al. (2010), and references therein.

According to the combined zircon U–Pb SHRIMP dating and Hf isotope determinations of Tunik et al. (2010), in the Rayoso

Table 3
Possible timing of exposure of some juvenile Tonian magmatic rocks in Argentina (units with dated detrital zircons lacking Hf isotope determinations not included in table; see text).

(Meta)-sedimentary unit and location	Depositional age	Juvenile Tonian population	Reference
Santa Helena Schist, La Pampa	556 to 530–520 Ma	999–871 Ma; ϵ_{Hf} +2.28 to +5.73	Zappettini et al. (2010)
Green Schist, southern San Luis	500 to 465 Ma	966–921 Ma; ϵ_{Hf} +3.08 to +6.51	Chernicoff et al. (2007, 2008a)
Cochrane Unit—Bahía de la Lancha Formation, SW Patagonia	Carboniferous (>310 Ma)	989–866 Ma; ϵ_{Hf} +0.7 to +5.7	Augustsson et al. (2006)
Rayoso Formation, Neuquén	ca. 125–ca. 105 Ma (Aptian-Albian)	850 Ma; ϵ_{Hf} +7.66	Tunik et al. (2010)

Formation there is a Tonian zircon of juvenile character (850 Ma; ϵ_{Hf} +7.66).

In the overlying Candeleros Formation there are no Tonian zircon grains; yet, the original source from which most of the Cretaceous (110–130 Ma) zircon grains crystallized was Tonian and juvenile (940–960 Ma; ϵ_{Hf} +1.44 – +2.19). Also, a Lower Permian zircon crystallized from a juvenile Tonian source (950 Ma; ϵ_{Hf} +3.76).

5.5. Other Tonian detrital zircons

Some of the Tonian detrital zircon populations that still lack Hf isotope studies may be derived from juvenile sources. Two possible cases are those from the El Jagüelito and Nahuel Niyeu Formations, i.e. two Cambrian metasedimentary units of the North-Patagonian region (see 3.f, above). Another two cases could come from, e.g. Las Piedras and Negro Peinado Formations.

The Las Piedras Formation, La Pampa province (Ediacaran-Lower Cambrian: ca. 555 to ca. 525 Ma; Chernicoff et al., 2010b) contains a zircon grain dated at ca. 965 Ma.

The Negro Peinado Formation, La Rioja province (<ca. 505 Ma; Cambrian-Ordovician? depositional age; e.g. Collo et al., 2009) contains a small group of Tonian zircon grains dated at 985–883 Ma.

6. Discussion

Juvenile magmatic units pertaining to the time interval lasting from 1000 to 850 Ma, i.e. Tonian (Early Neoproterozoic) are presently not exposed in Argentina. However, Hf isotope determinations on Palaeozoic magmatic units carried out by the present authors, together with the compilation of both Hf and Nd isotope studies from previous work, permits to associate, *geochronologically* the juvenile Tonian crust from which the rock units referred to in the text were derived, with the extensional events that occurred at the end of the Mesoproterozoic, globally related with the diachronous breakup of the Rodinia supercontinent. Although, *spatially*, this association is more difficult to solve, it should be expected that, at least in the vast regions of central Argentina, likely to be underlain by an autochthonous Paleo-Mesoproterozoic orogen (Chernicoff et al., 2010c), the inferred presence of juvenile Tonian magmatic rocks could indicate zones of thinned crust that somehow record the extensional tectonics occurred at that time. Evidence of the protracted character of this process is given by the identification of two discrete rifting events at the Western Sierras Pampeanas, the earliest being at Late Mesoproterozoic = Stenian (ca. 1070 Ma; massif-type anorthosites; Casquet et al., 2005), and the latest being at Middle Neoproterozoic = Cryogenian (ca. 774 Ma; A-type orthogneisses; Baldo et al., 2006). Palaeozoic metaigneous rocks of La Pampa studied in the present work, together with other magmatic rock units of varied ages compiled in this article would point to the same extensional context largely occurred during the Tonian period, e.g. Puna region, northern Precordillera (Sierra de Maz), etc.; (cf. Fig. 1).

The possibly complex geometry of the unexposed interconnected rifts –like those thought to have heralded the formation of a series of stepped pull-apart basins that became the depositional loci for several volcano-sedimentary successions involved in the formation of the Brasiliano/Pan-African branched system of orogens (Silva et al., 2008, and references therein)– is beyond the scope of the present work due to insufficient data. Nonetheless, it is worth mentioning that these zones with indirect evidence of thinning and rifting notably coincide with Paleozoic suture zones –e.g. boundaries between Antofalla and Pampia terranes, between Cuyania and Chilenia terranes, and between Pampia and the Rio de la Plata Craton– and related back-arc extensional belts (e.g. Famatinian mafic belts from Puna and from La Pampa), their location thus pointing to a possible control exerted by old precursor crustal discontinuities.

By comparison with the São Francisco craton, where representative Tonian rock types are exposed and well known, we consider that the juvenile Tonian sources of the magmatic rock units presented in this article could be assigned mainly to the Extensional Events II and III defined in that craton (Tupinambá et al., 2007). According to the latter authors, Extensional Events I, II and III peak at 1120–1000 Ma, 930–900 Ma, and 850–815 Ma respectively. The Events I and II are characterized mostly by mafic dykes and, to a lesser extent, by hypabyssal and intrusive mafic bodies. The Event II was followed by the intrusion of A-type granite-gabbro suites. The Event III is characterized by the predominance of MORB-type oceanic rocks and the absence of continental magmatic rocks (indicated by the relatively lack of 850 to 815 Ma detrital zircons in the sedimentary basins), therefore this event would probably be related to the oceanic phase of Rodinia breakup.

Further Hf isotope studies on dated zircons of magmatic rocks from La Pampa and other locations, together with the examination of the inherited magmatic zircons in sedimentary rocks and the Hf isotope determinations on dated detrital zircon grains, should in future help with the indirect identification of the juvenile Tonian rocks –and the geometry of the related extensional structures – in Argentina.

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