Neoproterozoic A-type magmatism in the Western Sierras Pampeanas (Argentina): evidence for Rodinia break-up along a proto-Iapetus rift?

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ABSTRACT

A-type orthogneisses of mid Neoproterozoic age (774 ± 6 Ma, U-Pb SHRIMP zircon age), are reported for the first time from the Grenvillian basement of the Western Sierras Pampeanas in Argentina. These anorogenic meta-igneous rocks represent the latest event of Rodinia break-up so far recognized in Grenvillian basement exposures across Andean South America. Moreover, they compare well with A-type granitoids and volcanic rocks along the Appalachian margin of Laurentia (Blue Ridge), thus adding to former evidence that the Western Sierras Pampeanas Grenvillian basement was left on the conjugate rifted margin of eastern Laurentia during Rodinia break-up and the consequent opening of the Iapetus ocean.

Introduction

Piper (1976) first suggested that the continental masses were once reunited in a supercontinent at the end of the Mesoproterozoic. Evidence for this supercontinent, that was called Rodinia by McMenamin and McMenamin (1990), has since been growing (for reviews see Meert and Torsvik, 2003; Pisarevsky *et al.*, 2003). Amalgamation of Rodinia took place by successive ocean consumption, arc collision and eventually continental collision, resulting in the worldwide Grenville orogeny between ca. 1.3 and 1.0 Ga (Hoffman, 1991). Rodinia subsequently broke up during the Neoproterozoic, but the timing of this process is poorly known. Many continental margins resulting from Rodinia break-up were subsequently involved in younger mobile belts, so that evidences such as extensional structures and syn-rift sedimentary fillings were largely overprinted by new tectonic fabrics and masked by younger magmatism and metamorphism. A-type granitic rocks however remain as good evidence for rifting, as they are typical of anorogenic extensional settings (e.g. Eby, 1990), preserve their chemical features unmodified irrespective of metamorphic grade, and can be readily dated by precise U-Pb geochronology. We report here Neoproterozoic ca. 774 Ma orthogneisses representing volcanic or subvolcanic A-type magmatism in the Grenvillian basement of the Western Sierras Pampeanas in Argentina (Baldo *et al.*, 2005) (Fig. 1a). This magmatism attests to an earlier phase of rifting in Rodinia, during the 200 Myr preceding the opening of the Iapetus ocean (Bartholomew and Tollo, 2004). This event is recognized for the first time in Andean South America, where remnants of Grenville-age basement are preserved in Colombia, Perú, eastern Bolivia and the Western Sierras Pampeanas of Argentina.

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Geological Setting

Grenville-age basement in the Western Sierras Pampeanas, thoroughly rejuvenated during the Famatinian orogeny in the Early to Middle Ordovician, has been recognized from a number of orthogneisses dated at ca. 1.0–1.1 Ga (Dalla Salda and Varela, 1984; McDonough *et al.*, 1993; Pankhurst and Rapela, 1998), detrital zircon ages (Casquet *et al.*, 2001), an ophiolite complex of ca. 1.2 Ga (Vujovich *et al.*, 2004), massif-type anorthosites of ca. 1070 Ma (Casquet *et al.*, 2005a) and granulite facies metamorphism of ca. 1.2 Ga (Casquet *et al.*, 2006). This orthogneissic basement is overlain by an epeiric metasedimentary sequence of carbonate and siliciclastic rocks (the Difunta Correa sedimentary sequence of Baldo *et al.*, 1998), which is late Neoproterozoic in age (Galindo *et al.*, 2004) and contains detrital zircons of likely Gondwana provenance (Rapela *et al.*, 2005).

The Western Sierras Pampeanas Grenville-age outcrops are generally considered to represent the basement of the Precordillera (or Cuyania) terrane, i.e. an exotic continental block that allegedly rifted away from the Ouachita embayment of Laurentia in late Neoproterozoic–Early Cambrian times, and collided with the proto-Andean margin of Gondwana in the Ordovician to produce the Famatinian orogeny (for a review of the Precordillera terrane hypothesis, see Thomas and Astini, 2003; Ramos, 2004). The terrane has a passive margin carbonate sequence of early Cambrian to early Ordovician age, exposed in the Argentine Precordillera to the west of the Sierras Pampeanas (Fig. 1a), which contains faunas akin to those of the late Neoproterozoic eastern Laurentia rifted margin. Allochthoneity of the Western Sierras Pampeanas basement has, however,

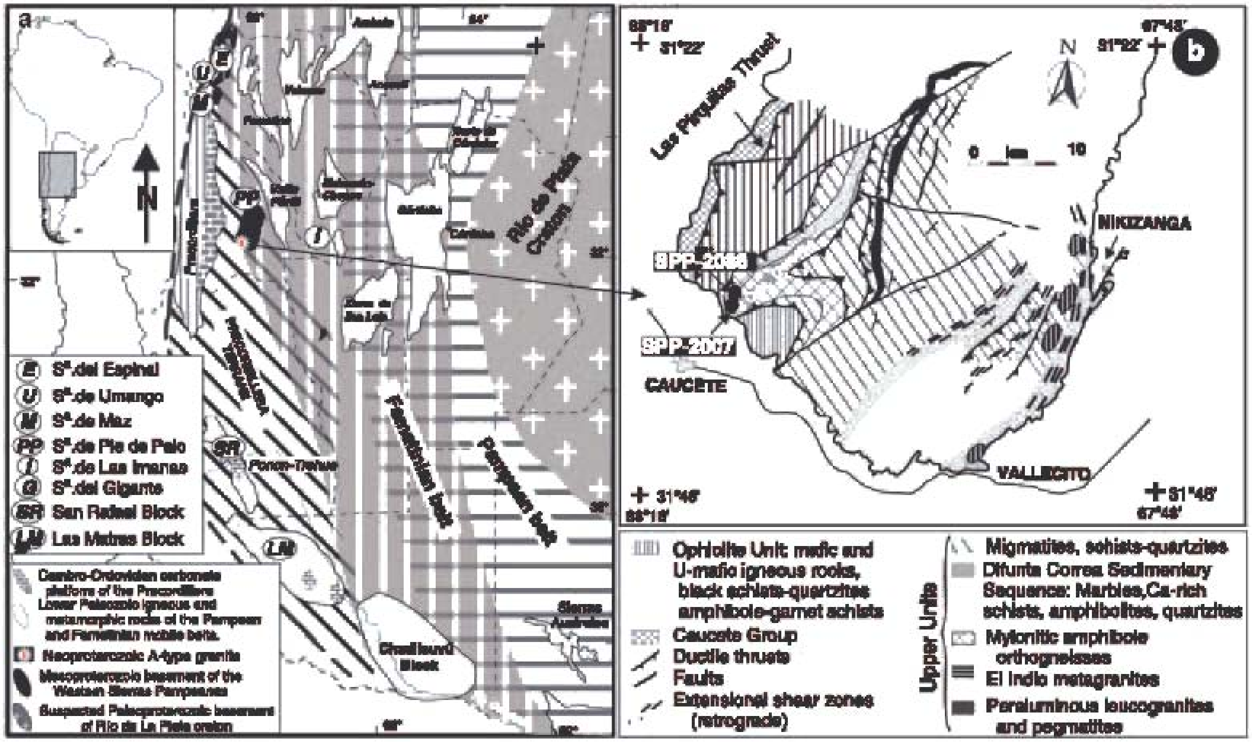

Fig. 1 (a) Sketch map showing location of the Sierra de Pie de Palo, Western Sierras Pampeanas, the Precordillera Terrane and main orogenic belts. (b) Geological map of southern Sierra de Pie de Palo, and sampling location.

been recently questioned (e.g. Galindo *et al.*, 2004).

The Sierra de Pie de Palo (Fig. 1b) is one of the Western Sierras Pampeanas where Grenville-age rocks were first recognized. The sierra consists of stacked nappes thrust westwards during the Famatinian orogeny: each one consists of both Grenville-age basement and the Difunta Correa sedimentary sequence, which underwent penetrative deformation (folding, foliation development and ductile shearing) and relatively high-pressure low-temperature Famatinian metamorphism. The nappes rest upon the almost unmetamorphosed Precordillera passive margin sequence of early Cambrian age (Galindo *et al.*, 2004) below the Pirquitas basal thrust (Ramos *et al.*, 1996). The lowermost nappe contains a Grenville-age ophiolite of ca. 1.2 Ga (Vujovich *et al.*, 2004; and references therein). Above this nappe is a wide shear zone where rocks of the Difunta Correa metasedimentary sequence and A-type orthogneisses are thoroughly interleaved. Relative age relationships are confused by the strong deformation.

Sampling and Petrography

Two samples of a mylonitic orthogneiss (SPP-2007 and SPP-2086) were collected at the mouth of the Quebrada Derecha (31°35′52″S, 68°13′57″W) (Fig. 1b), for chemical analysis (major and trace elements) and isotope (Sr and Nd) geochemistry. SPP-2007 was chosen for U-Pb SHRIMP zircon dating. This orthogneiss is interleaved with epidote-bearing garnet micaschists (Qtz, Ms, Bt, Pl, Grt, Ep, ±Amph; mineral abbreviations as in Kretz, 1983), black quartzites (Qtz, Pl, Bt, ±Ms), amphibole-garnet schists (Qtz, Pl, Amph, Grt, Ep, Ms, ±Bt), garnet amphibolites (Hbl, Pl, Grt, Ep, ore minerals) and minor marble.

The orthogneiss consists of Qtz, Kfs (Or_{95}, Ab_{4-5}), Pl (An_3, Ab_{97}), Bt (X_{Fe} = 0.83, F = 0.43%), Grt (Alm_{36-40}, Grs_{35-44}, Sp_{18-24}, $And_{2.9-3.6}$, $Py_{0.5-0.7}$), Fe-pargasite (K_2O = 2.2–2.6%; Na_2O = 1.9–2.2%), Ep (Ps_{42}), Ttn, Aln, Zrn, Mnz, Ap, Py and Mag. Representative chemical compositions of minerals are shown in Table 1. The garnet contains inclusions of epidote, quartz and plagioclase; its high Mn content might in itself suggest an igneous origin, but as the overall rock composition is metaluminous it is more likely that it formed through metamorphic reactions. Garnet amphibole thermometry (Ravna, 2000) provides T-values between 620 and 550 °C, but values obtained from garnet biotite exchange thermometry (Holdaway, 2001) are in the range of 400–410 °C.

Texturally the orthogneiss consists of σ-type porphyroclasts of mainly pinkish K-feldspar (1–3 cm crystals) and medium-grained plagioclase, garnet, epidote and amphibole, all wrapped around by a foliated fine-grained dark groundmass of dynamically recrystallized quartz and biotite (Fig. 2). Composite S-C′ foliations (Fig. 2) and σ-type kinematic markers suggest that relative movement within the shear zone was top-to-the-southwest (present coordinates). Younger open folds of variable size with almost horizontal N80°E axes are common in this part of the sierra.

Geochemistry

Chemical analyses (Table 2) were performed at ACTLABS (Canada). Sr

Table 1 Representative chemical composition of minerals of orthogneiss SPP-2007.

wt%	Grt		Bt		Pl		Kfs		Hbl		Ep
SiO_2	37.37		35.76		66.27		63.71		37.56		36.41
TiO_2	0.04		2.46		0.01		0.01		0.46		0.05
Al_2O_3	20.46		14.57		20.39		18.51		13.08		22.98
Cr_2O_3	0.00		0.01		0.00		0.00		0.03		0.00
FeO	20.01		28.95		0.11		0.10		28.31		13.03
MnO	8.01		0.42		0.04		0.00		0.50		0.35
ZnO	0.00		0.12		0.00		0.00		0.00		0.00
MgO	0.16		3.46		0.01		0.00		2.06		0.03
BaO	0.00		0.09		0.00		0.17		0.00		0.00
SrO	0.00		0.00		0.03		0.00		0.00		0.00
CaO	14.58		0.03		0.72		0.00		10.70		23.56
Na_2O	0.00		0.07		11.56		0.31		2.24		0.03
K_2O	0.00		9.58		0.10		16.42		2.28		0.00
F	0.12		0.42		0.00		0.00		0.22		0.00
Cl	0.00		0.00		0.00		0.00		0.00		0.00
Total	100.00		95.78		99.24		99.22		97.31		96.43
	12 Ox		24 Ox		32 Ox		32 Ox		23 Ox		12.5 Ox
TSi	2.064	Si	6.000	Si	11.729	Si	11.916	Si	6.721	Si	2.484
TAl	0.036	Al^{IV}	2.000	Al	4.249	Al	4.078	Al^{IV}	1.279	Al^{IV}	0.516
Al^{VI}	1.675	Al^{VI}	0.878	Ti	0.001	Ti	0.001	Al^{VI}	1.477	Al^{VI}	1.331
Ti	–	Ti	0.312	Fe^2	0.017	Fe^2	0.015	Cr	0.004	Ti	0.003
Cr	0.002	Fe^2	4.063	Mn	0.006	Mn	0.000	Ti	0.062	Fe^3	1.337
Fe^2	1.327	Cr	0.001	Mg	0.003	Mg	0.000	Mg	0.548	Cr	0.000
Mg	0.018	Mn	0.059	Ba	0.000	Ba	0.012	Fe^2	4.237	Mn	0.020
Mn	0.538	Mg	0.866	Sr	0.000	Sr	0.000	Mn	0.075	Mg	0.003
Ca	1.239	Zn	0.010	Ca	0.137	Ca	0.000	Ca	0.506	Ca	1.722
Na	–	Ba	0.006	Na	3.068	Na	0.113	Ca	1.456	Na	0.003
Alm	42.51	Ca	0.005	K	0.022	K	3.918	Na	0.776	K	0.000
Grs	39.68	Na	0.022	An	3.30	Or	97.20	K	0.520	Ps	42
Py	0.59	K	2.051								
Sps	17.23	XMg	0.18								

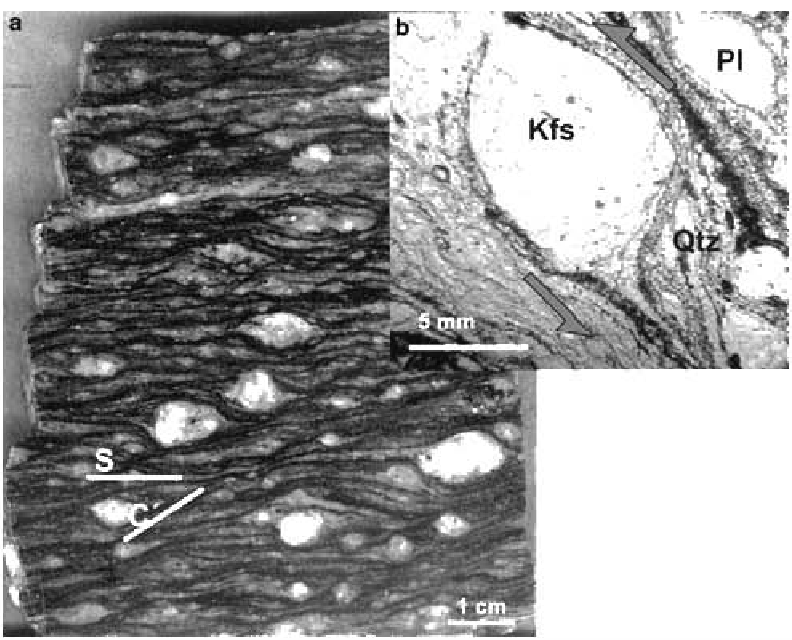

Fig. 2 (a) Mylonitic texture of SPP-2007 orthogneiss with S-C'composite foliations (section parallel to L_{myl}). (b) Asymmetric Kfs porphyroclasts in a fine-grained groundmass of dynamically recrystallized quartz and biotite.

Table 2 Representative chemical and isotopic compositions of mylonitic orthogneisses from Sierra de Pie de Palo.

wt%	SPP-2007	SPP-2086
SiO_2	74.50	72.17
TiO_2	0.26	0.49
Al_2O_3	12.25	11.91
Fe_2O_3	2.95	4.26
MnO	0.05	0.07
MgO	0.19	0.38
CaO	0.98	1.61
Na_2O	3.32	3.45
K_2O	4.93	4.15
P_2O_5	0.05	0.11
LOI	0.42	0.44
Total	99.89	99.04
Ba	565	811
Rb	92.41	114
Sr	65.80	100
Y	52.4	64.4
Zr	338	516
Nb	22.1	29.8
Th	9.88	10.8
Pb	24	23
Ga	23	25
Zn	06	71
V	0	10
Hf	9.7	14.1
Cs	0.6	1.1
Sc	4	8
Ta	1.62	2.34
Co	2	4
Be	3	4
U	3.87	3.36
W	1.2	0.9
REE (p.p.m.)		
La	57.8	54.6
Ce	137	129
Pr	15.7	15.1
Nd	60.36	57.1
Sm	11.87	13.0
Eu	1.39	2.25
Gd	11.4	12.4
Tb	1.83	2.09
Dy	10.3	12.2
Ho	2.05	2.39
Er	6.39	7.88
Tm	1.04	1.22
Yb	6.35	7.49
Lu	0.88	1.02
Sum	3244	317.5
Isotopic ratios		
Sm/Nd	0.1066	0.2277
$^{147}Sm/^{144}Nd$	0.1189	0.1376
$^{143}Nd/^{144}Nd$	0.512457	0.512592
$^{143}Nd/^{144}Nd_{(774)}$	0.511854	0.511893
εNd_{774}	4.1	4.9
Tdm (Ga)	1.06	0.99
$Rb/Sr_{(wt)}$	1.4038	1.0556
$^{87}Rb/^{86}Sr$	4.0776	3.0620
$^{87}Sr/^{86}Sr$	0.748154	0.734428
$^{87}Sr/^{86}Sr_{(774)}$	0.703091	0.700589
εSr_{774}	−6.9	−42.4

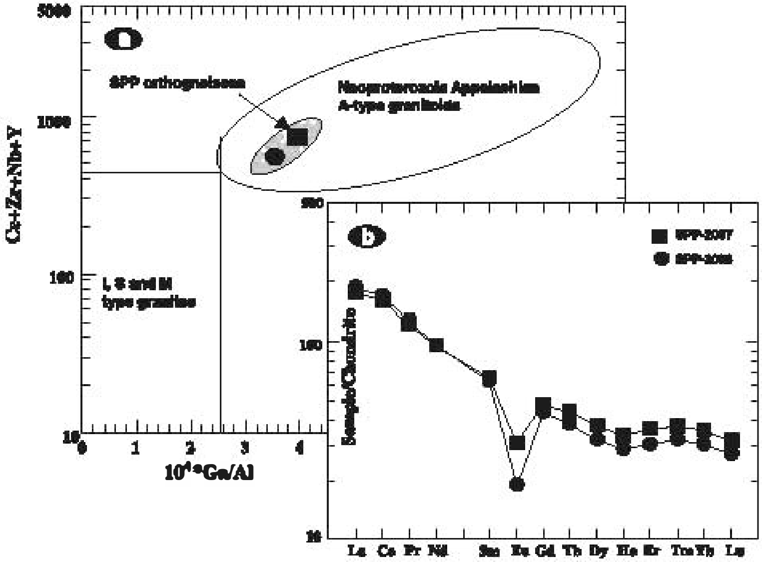

Fig. 3 (a) Plot of (Ce + Zr + Y) vs. $10^4 \times$ Ga/Al for Neoproterozoic A-type granites (Appalachian data from Tollo *et al.*, 2004) and the SPP orthogneisses. (b) Chondrite-normalized REE plot of SPP orthogneisses.

and Nd isotope compositions were obtained at the Geochronology and Isotope Geochemistry Centre at the Universidad Complutense of Madrid.

Chemically the orthogneisses are metaluminous acid rocks (SiO_2 = 72–74%; ASI = 0.90–0.97), but with a relatively high agpaitic index (0.85 and 0.88), high total alkalis (7.6 and 8.2%) and a ratio Fe_2O_{3total}/MgO of 11.2 and 15.5. These geochemical features are characteristic of A-type magmatism (Eby, 1990, 1992). This classification is strengthened by the relatively high values of the 10^4*Ga/Al ratio (3.5 and 3.9), along with high concentrations of HFS elements Y (52–64 p.p.m.), Nb (22–30 p.p.m.), Ta (1.62–2.34 p.p.m.), Ga (23–25 p.p.m.) and Zr (338–516 p.p.m.) (Fig. 3a). As the alkali content may reflect the effect of metamorphism, high-silica igneous rocks are often classified using HFS element abundances: low-Zr rocks (>300 p.p.m.) are termed 'subalkaline' whereas high-Zr rocks (>350 p.p.m.) are classed as 'peralkaline' (Leat *et al.*, 1986). The high Zr content of the orthogneisses clearly indicates an alkaline affinity for the igneous protoliths. These rocks are moderately enriched in LREE ($[La/Yb]_N$ = 4.9–6.1) and show a remarkable Eu-negative anomaly (Eu/Eu* = 0.36–0.54) (Fig. 3b), suggesting plagioclase fractionation. Furthermore, their REE pattern is very similar to that reported for A-type granites (e.g. Scheepers, 2000; Tollo *et al.*, 2004; Dahlquist *et al.*, 2006). $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ values at the age of crystallization of 774 Ma (see below) (Table 2) are between 0.511854 and 0.511893, corresponding to a mean εNd_{774} value of +4.2, and between 0.7031 and 0.7006 respectively. The multi-stage Nd model age (T_{DM}) is 1060 Ma. Rb–Sr systematics in metamorphic rocks are highly susceptible to disturbance, and the lower $^{87}Sr/^{86}Sr$ value (below the Bulk Earth value of 0.7036 at the crystallization age) might result from subsolidus alteration during the overprinting by Famatinian deformation and metamorphism. The other value, and the two Nd isotope compositions, are taken as indicative of a primitive source, which is not uncommon for A-type magmatism (e.g. Kebede and Koeberl, 2003; Mushkin *et al.*, 2003).

U-Pb Geochronology

A heavy mineral concentrate was prepared from sample SPP-2007 at NERC Isotope Geosciences Laboratory, Keyworth, by disc-milling and panning, followed by standard heavy liquid and magnetic procedures. Approximately 100 zircon grains were hand-picked from the mineral concentrate, mounted in epoxy together with chips of reference zircons FC1 and SL13, ground approximately half-way through and polished. Reflected and transmitted light photomicrographs, and cathodo-luminescence (CL) SEM images, were used to decipher the internal structures of sectioned grains and to target specific areas within the zircons.

U-Th-Pb zircons analyses were made using SHRIMP II, each analysis consisting of six scans through the mass range. The data were reduced in a manner similar to that described by Williams (1998, and references therein), using the SQUID Excel Macro of Ludwig (2000).

Zircons from sample SPP-2007 range from euhedral grains with pyramidal terminations to subhedral forms with somewhat ragged terminations. The grains are mostly elongate with an average length/breadth ratio of about 2 : 1. A number of grains have tube-like central cavities that are commonly observed in rapidly crystallized zircon from a volcanic to subvolcanic setting. The CL images reveal mostly zoned igneous zircon, though internal discontinuities are present and little-to-unzoned central areas are another feature commonly seen in volcanic crystals. Bright luminescent rims are interpreted as part of the same single igneous crystallization event. However, some more ragged grain shapes reflect modification during metamorphism, even though no significant new zircon developed. Measurements were made by analysing 14 areas; the luminescent rims were too thin to permit analysis. A summary of the results is listed in Table 3 and shown in a Tera Wasserburg plot (Fig. 4b). Uncorrected data mostly fall in a tight group close to Concordia, signifying that common Pb contents are very low. Ignoring one low apparent age (740 Ma), the ^{207}Pb-corrected $^{206}Pb/^{238}U$ results yield a consistent mean of 774 ± 6 Ma (95% confidence limit including uncertainty in the reference zircon U/Pb ratio calibration; MSWD = 0.75). This age is taken to represent the crystallization of the igneous protolith of the orthogneiss.

Discussion

The significant time gap between the end of the Grenville-age orogeny in

Table 3 U-Pb SHRIMP data for zircons in SPP-2007.

Grain spot	U (p.p.m.)	Th (p.p.m.)	Th/U	Pb* (p.p.m.)	$^{204}Pb/^{206}Pb$	f_{206}%	Total $^{207}Pb/^{206}Pb$	± 1σ	$^{238}U/^{206}Pb$	± 1σ	Radiogenic $^{206}Pb/^{238}U$	± 1σ	Age (Ma) $^{206}Pb/^{238}U$	± 1σ
1.1	212	54	0.25	20	0.000157	0.21	0.0669	0.0007	7.835	0.129	0.1274	0.0021	772.9	12.0
1.2	305	82	0.27	29	0.000285	0.17	[illegible]	0.0008	7.806	0.105	0.1264	0.0017	767.4	9.6
2.1	374	125	0.33	37	0.000107	<0.01	0.0645	0.0006	7.793	0.092	0.1284	0.0015	778.9	8.7
3.1	45	15	0.33	4	–	<0.01	[illegible]	0.0025	7.913	0.400	0.1265	0.0064	767.7	36.8
4.1	175	47	0.27	17	0.000285	0.02	0.0654	0.0008	7.824	0.113	0.1278	0.0019	775.2	10.6
5.1	113	29	0.25	11	0.000160	0.17	[illegible]	0.0011	7.731	0.113	0.1291	0.0019	782.9	10.8
6.1	218	60	0.27	21	0.000124	0.17	[illegible]	0.0008	7.962	0.111	0.1254	0.0018	761.5	10.1
7.1	370	123	0.33	36	0.000013	0.06	0.0657	0.0004	7.760	0.100	0.1288	0.0017	780.9	9.5
8.1	46	11	0.25	4	0.001298	0.27	0.0674	0.0014	7.727	0.156	0.1291	0.0026	782.6	14.9
9.1	120	30	0.25	12	−0.000004	0.16	0.0665	0.0013	7.709	0.116	0.1295	0.0020	785.1	11.2
10	292	106	0.36	29	0.000129	0.05	0.0656	0.0006	7.717	0.092	0.1295	0.0016	785.2	8.9
11	257	86	0.33	25	0.000256	0.03	0.0654	0.0006	7.940	0.100	0.1259	0.0016	764.4	9.1
12	103	29	0.29	9	0.000290	0.02	0.0654	0.0006	8.220	0.127	0.1216	0.0019	740.0	10.9
13	211	58	0.28	20	0.000026	0.07	0.0658	0.0006	7.952	0.102	0.1257	0.0016	763.1	9.3

1. Uncertainties given at the 1σ level.
2. f_{206}% denotes the percentage of ^{206}Pb that is common Pb.
3. Correction for common Pb made using the measured $^{238}U/^{206}Pb$ and $^{207}Pb/^{206}Pb$ ratios following Tera and Wasserburg (1972) as outlined in Williams (1998).
4. Pb/U ratios were normalized relative to a value of 0.1859 for the $^{206}Pb/^{238}U$ ratio of the FC1 or AS3 reference zircons, equivalent to an age of 1099 Ma (see Paces and Miller, 1993).

Pb* — Radiogenic Pb

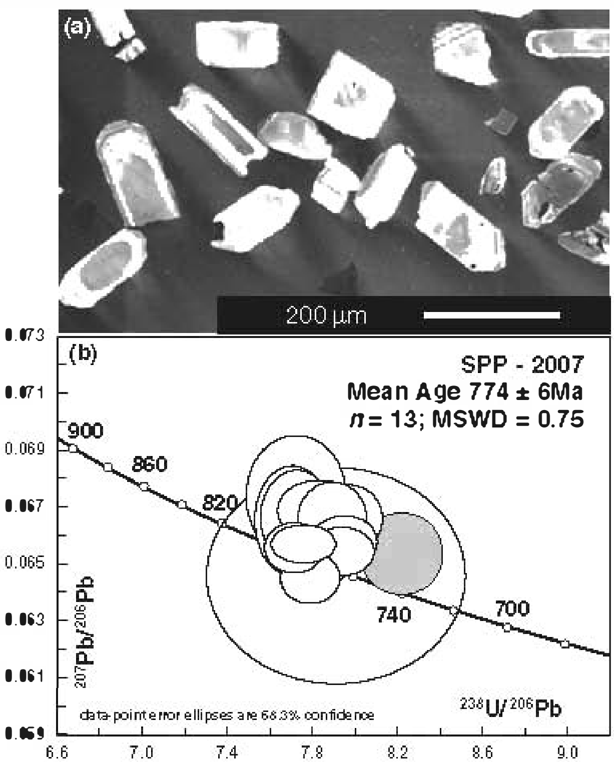

Fig. 4 (a) Cathodoluminescence images of SPP-2007 zircons showing unzoned cores, magmatic oscillatory-zoned overgrowths and a thin luminescent rim. (b) Tera–Wasserburg diagram of the full dataset showing error ellipses at 68.3% confidence limits for igneous cores and rims.

the Western Sierras Pampeanas and the A-type magmatism in the Sierra de Pie de Palo, attests to a post-orogenic continental rifting setting at 774 ± 6 Ma. This is the youngest anorogenic magmatic event of Neoproterozoic age so far recognized in this part of the pre-Andean basement. Older igneous events that were probably also post-orogenic have been recorded from the Western Sierras Pampeanas basement at ca. 1070 Ma (massif-type anorthosites; Casquet *et al.*, 2005a) and ca. 845 Ma (Casquet *et al.*, 2005b), perhaps representing discrete rifting events during protracted break-up of Rodinia. The A-type orthogneisses are thus probably indicative of the final stage of break-up and constitute the first indication of this event so far recognized in South America, where remnants of Grenville-age basement exist in Colombia, Perú, eastern Bolivia and Argentina.

The timing of break-up across the Rodinia supercontinent is still poorly known in detail. However, ages between 850 and 700 Ma have been recorded for extensional mafic magmatism, bimodal magmatism, and A-type or other granites from many different

gins, and are similarly considered indicative of Rodinia break-up. Typical examples of this are in the Canadian Arctic (Shellnutt *et al.*, 2004), southern and central Australia (Wingate *et al.*, 1998), Baltica (Pease and Bogdanova, 2003), the Scandinavian Caledonides, Scotland and Taimyr (Paulsson and Andreasson, 2002; Cawood *et al.*, 2004), the Yangtze craton and South China (Wenli *et al.*, 2003), the North China block (Zhai *et al.*, 2003), South Korea (Lee *et al.*, 2003) and eastern Egypt (Loizembauer *et al.*, 2001).

Of particular relevance to our case is the Neoproterozoic A-type magmatism recorded along the Appalachian margin of Laurentia in the Blue Ridge province. In recent paleogeographical reconstructions of Rodinia (e.g. Loewy *et al.*, 2003), eastern Laurentia is placed alongside Amazonia, whose southern extension (present coordinates) is represented by the Arequipa-Antofalla block of Perú, northern Chile and Argentina, accreted to Amazonia during the Grenville age-equivalent Sunsas orogeny (Loewy *et al.*, 2004), and probably also by the Western Sierras Pampeanas Grenvillian basement (Casquet *et al.*, 2005a,b). A remarkable event of A-type granitic magmatism and bimodal volcanism has been long recognized in the Blue Ridge province of Virginia and North Carolina with crystallization ages between 765 and 680 Ma (Tollo *et al.*, 2004, and references therein). Protracted north-migrating rifting accompanied by A-type magmatism, continued along the Appalachian margin of Laurentia until 572–564 Ma when Iapetus was created (Bartholomew and Tollo, 2004). The older Blue Ridge ages are slightly younger than the age determined here for the Sierra de Pie de Palo orthogneisses. Thus, in the hypothesis of an Amazonia-Arequipa Antofalla-Western Sierras Pampeanas–eastern Laurentia connection within the Rodinia supercontinent, the Sierra de Pie de Palo A-type orthogneisses might thus represent an earlier rifting event still farther south. This similarity between the two margins is additional to the already recognized parallels between massif-type anorthosites in the Western Sierras Pampeanas and the Appalachian Blue Ridge and the Piedmont provinces (Casquet *et al.*, 2005a). The evidence presented here thus strengthens the hypothesis that the Appalachian margin of Laurentia and the western margin of Amazonia – and its southern extension into the Western Sierras Pampeanas – were conjugate-rifted margins in the mid Neoproterozoic. Drifting across these margins subsequently led to the opening of the Iapetus ocean.

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