Grenvillian massif-type anorthosites in the Sierras Pampeanas

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We report the discovery of massif-type anorthosites in the Andean basement of the Western Sierras Pampeanas of Argentina. U–Pb zircon dating (by sensitive high-resolution ion microprobe) of a cogenetic gabbronorite dyke yields ages of 1070 ± 41 Ma for igneous emplacement and 431 ± 40 Ma for metamorphism. These anorthosites are petrologically and geochemically comparable with those of the Grenville province of Laurentia. Palaeogeographical reconstructions of Rodinia at 1.0–1.1 Ga suggest that the Sierras Pampeanas anorthosites were part of a large anorthosite province in the late Mesoproterozoic.

Keywords: Sierras Pampeanas, Argentina, Neoproterozoic, Rodinia, SHRIMP data, anorthosites.

Massif-type anorthosites are abundant in the worldwide Grenvillian mobile belt (1.0 1.2 Ga) resulting from the assembly of the Mesoproterozoic supercontinent of Rodinia (Ashwal 1993), especially along the Appalachian margin of Laurentia (North America). With the break-up of Rodinia, former clusters of anorthosite massifs were dispersed in several continents. Palaeogeographical reconstructions at *c.* 1 Ga mostly place the eastern margin of Laurentia against the western margin of South America. Here we show for the first time that massif-type anorthosites of Grenvillian age also occur in SW South America as part of the basement of the modern Andean chain, establishing its characteristic Grenvillian lithology and consistent with the idea that a continuous Grenvillian orogenic belt existed between the two areas.

The Western Sierras Pampeanas. Tectonically, the Western Sierras Pampeanas of Argentina (Fig. 1) are located between western Gondwana and the Precordillera terrane, an exotic continental fragment rifted either from the Appalachian margin of Laurentia (Thomas & Astini 1996; Dalziel 1997) or from elsewhere in Gondwana (Aceñolaza *et al.* 2002) and accreted to the proto-Andean margin of Gondwana in the Mid-Ordovician. Grenvillian ages of 1.0 1.1 Ga have been reported from the Western Sierras Pampeanas (Pankhurst & Rapela 1998; Ramos *et al.* 1998; Casquet *et al.* 2001), usually considered to represent the otherwise unexposed basement of the Precordillera terrane. However, it seems equally possible that they could be an integral part of the Gondwana margin (Galindo *et al.* 2004). Our new discovery does not resolve this problem, but is clearly compatible with palaeogeographical models that place Laurentia and western Gondwana facing each other in the late Mesoproterozoic regardless of whether either the Precordillera or the Western Sierras Pampeanas are truly allochthonous.

In the sierras of Maz and Espinal we recognize at least three anorthosite massifs with areas of 9.5, 11.6 and 29.9 km^2; one, of difficult access, is only inferred from LANDSAT images. The bodies are lenticular, elongated north south, and set in amphibolite-facies metamorphic rocks of unknown age (Lucassen & Becchio (2003) reported U Pb titanite metamorphic ages of 530 420 Ma). Ductile shear zones concordant with the moderate-to-steep east-dipping regional foliation occur along the contacts of the plutons and within them. Deformation of the plutons outside the shear zones is very weak.

Petrology and geochemistry of the anorthosites. Coarse-grained anorthosite is the predominant rock type in these bodies, and is cut by metagabbro dykes. Also probably related is a magnetite apatite-rich rock (nelsonite) near one of the Maz massifs. They show a first generation of large, roughly aligned, relict igneous plagioclase crystals (chiefly andesine, although the compositional range is $Ab_{42\ 76}$ $An_{24\ 57}$ $Or_{<1.5}$), surrounded by fine-grained polygonal recrystallized plagioclase. The main prograde mafic minerals are amphibole and garnet ($Alm_{53.0\ 63.5}$ $Grs_{19\ 38}$ $Py_{6\ 15}$ $Sps_{1\ 8}$), commonly in a corona-like arrangement with framboidal garnet surrounding amphibole cores. Peak metamorphic amphiboles are of two types: the more abundant has compositions near the join Fe-tschermarkite Fe-pargasite Fe-hornblende; the other is cummingtonite, often surrounded by amphibole of the first type and garnet. Other minerals probably stable during peak metamorphic conditions are biotite, titanite, ilmenite, apatite, and sometimes quartz and graphite. Chlorite, carbonates, epidote, tremolite, sericite and clay minerals are secondary.

Whole-rock analyses for anorthosites and a related mafic dyke are given in the Supplementary Publication (SUP. 18214, 3 pages, available from the Society Library or the British Library Document Supply Centre, Boston Spa, Wetherby, West Yorkshire LS23 7BQ, UK, or online at http://www.geolsoc.org.uk/SUP18214). The anorthosites have high Al_2O_3 (24 27%) and Sr (742 870 ppm), and low to moderate K_2O (0.4 1.5%), with Cr and Co mostly below detection limit. They display moderately

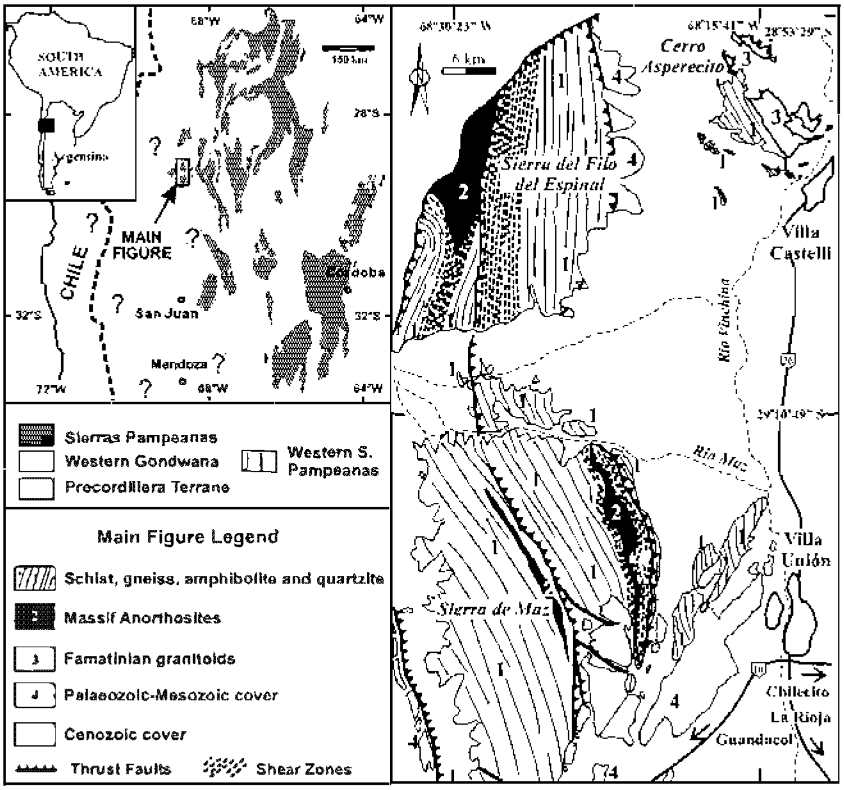

Fig. 1. Geological sketch map of the sierras of Maz and Espinal. Main inset shows location of the studied region in NW Argentina.

light rare earth element (LREE)-enriched chondrite-normalized patterns (La/YbN = 8–27) and positive Eu anomalies (Eu/Eu* = 3–14) (Fig. 2), typical of massif-type anorthosites in the Grenville province (Ashwal & Seifert 1980; Owens & Dymek 1992; McLelland *et al.* 1994). The mafic dyke is enriched in FeO, TiO_2, MgO, P_2O_5, Zr, Hf and Ta, and depleted in Al_2O_3, Na_2O and Sr; it is enriched in total REE with a slight negative Eu anomaly (Eu/Eu* = 0.9). Sr and Nd isotope compositions are variable ($\varepsilon Nd_{init} = +3.4$ to -1.2; initial $^{87}Sr/^{86}Sr$ ratio 0.7041–0.7059), indicating a probable mantle source with moderate crustal contamination. Nd model ages (T_{DM}) are 1.2–1.5 Ga. The mafic dyke is similar to a secondary lithology in the Mid-Proterozoic anorthositic massifs of Laurentia and Baltica: P_2O_5- and TiO_2-rich mafic differentiates classified as oxide–apatite gabbronorite (OAGN) and/or jotunite, usually considered as late-stage residual liquids (e.g. Cotkin 1997). In the Sierra de Maz a comagmatic relationship is supported by a viable trace element fractional crystallization model. The modelled magma after 91.5% crystallization of an anorthositic cumulate similar to MAZ-7211 is almost identical to the SiO_2-poor dyke rock MAZ-7210 (Fig. 2). Zr behaves incompatibly, being strongly depleted in the plagioclase cumulates and enriched only in the residual liquids where zircon crystallizes as a separate mineral. Thus OAGN or jotunites are suitable targets for U–Pb dating of comagmatic anorthosite complexes, as shown here. Whereas no zircon was found in the anorthosites, the mafic dyke MAZ-7210 contains anhedral to globular grains and clusters of clear colourless zircon up to 250 µm in size. Cathodoluminescence (CL) imaging (Fig. 3) reveals dark rims <30 µm thick on sector-zoned luminescent cores typical of igneous zircon crystallization in gabbroic rocks. The sharply defined luminescent rims are interpreted as metamorphic in origin. The anhedral to globular morphology is thus due to overgrowth on pre-existing magmatic grains.

Geochronology. U–Pb zircon dating was carried out by sensitive high-resolution ion microprobe (SHRIMP) using SHRIMP II at ANU, Canberra, targeting 24 areas, including seven core–rim pairs (see the Supplementary Publication, as above). In the Tera–Wasserburg diagram (Fig. 3) the data clearly form two groups; the rim data indicate a Palaeozoic age whereas the cores are Proterozoic. The vertical dispersion of both groups reflects the presence of significant common Pb not corrected for in this diagram, accentuated by the low U contents of the zircons (<10 ppm in the rims; 10–150 ppm in the cores). The rims have extremely low Th contents and low Th/U ratios (mostly <0.05),

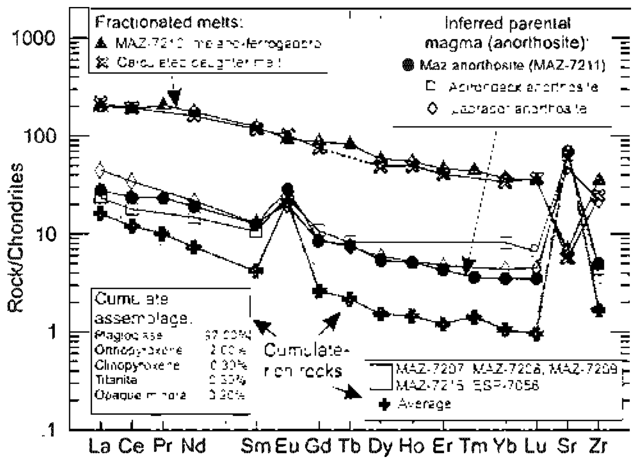

Fig. 2. Chondrite-normalized REE, Sr and Zr patterns of anorthosites from Maz and Espinal, showing modelled residual liquid by fractional crsytallization of the parental anorthosite magma to explain the origin of the gabbro dyke MAZ-7210 (see text for further details). Adirondack data from McLelland *et al.* (1994); Labrador data from Wiebe (1980).

compatible with a metamorphic origin. Correction for common Pb in the rims was made using the measured ^{207}Pb: extrapolated ^{206}Pb/^{238}U ages range from 399 ± 33 to 437 ± 20 Ma, with a weighted mean of 417 ± 16 Ma (Fig. 3). Because of the high common Pb contents, open-system loss of radiogenic Pb may be expected and regression of the data yields an intercept of 431 ± 40 Ma, possibly a better estimate for the timing of this event. This is younger than, albeit within error of, estimates of Famatinian metamorphism (e.g. *c.* 460 Ma, Casquet *et al.* 2001). Apart from one obviously disturbed age of 542 Ma, the ^{206}Pb/^{238}U ages of the cores range from 991 ± 11 to 1147 ± 29 Ma: 10 yield a mean of 1040 ± 10 Ma (MSWD = 1.2). In this case the best estimate for the primary crystallization age may be obtained from ^{207}Pb/^{206}Pb data: a 13-point discordia line in the Wetherill plot (Fig. 3), forced through a lower intercept of 431 ± 40 Ma, gives an upper intercept at 1070 ± 41 Ma. Three cores have older ^{207}Pb/^{206}Pb ages (after correction using ^{204}Pb) of 1234, 1374 and 1432 Ma that might represent slight disturbance of U–Pb systematics during metamorphism; these apparent ages are not considered significant.

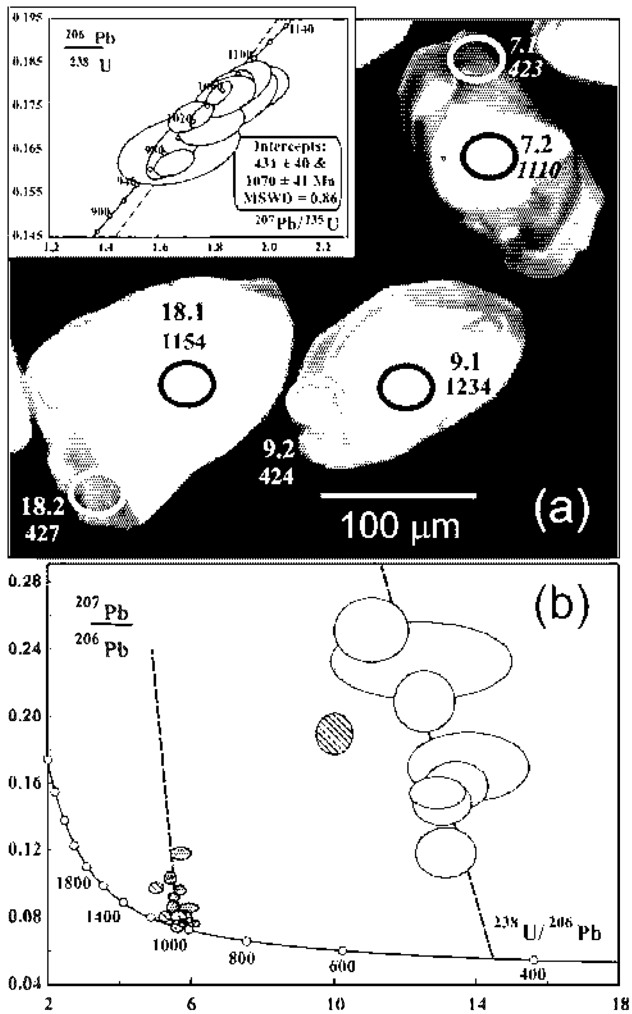

Fig. 3. (a) CL image of zircons from sample MAZ-7210 with spot numbers and determined U Pb ages. (b) Tera Wasserburg diagram of the full dataset, showing error ellipses at 68.3% confidence limits for the igneous cores (dark grey) and metamorphic rims (white); shaded spots are considered to be isotopically disturbed (see text). The dotted lines show the loci of common-Pb mixtures at *c.* 1070 and *c.* 430 Ma. The inset shows the upper intercept on a Wetherill concordia plot of the selected core data.

Comparison with Laurentian and other anorthosites. Our data show that the parent Maz and Espinal anorthosite magmas were emplaced 1030–1110 Ma ago. This embraces the age of Grenvillian anorthosites from the Appalachian margin of Laurentia, notably the Blue Ridge Roseland anorthosite (1045 ± 44 Ma, Pettingill *et al.* 1984) and the Piedmont (Goochland terrane) Montpelier anorthosite (1045 ± 10 Ma, Aleinikoff *et al.* 1996). Other similarities include Nd and Sr isotope compositions and T_{DM} values (Herz & Force 1984; Pettingill *et al.* 1984; Owens & Samson 2001), although the Argentine anorthosites are less potassic (0.4–1.5% K_2O, v. 2.8% for Roseland and 3.5% for Montpelier). Other massif-type anorthosites from the Grenville (Adirondacks and Quebec) and Nain provinces are apparently older than 1150 Ma (McLelland & Chiarenzelli 1990; Doig 1991), but those in the Oaxaquia terrane of southern Mexico (1012 ± 12 Ma, Keppie *et al.* 2003) and the Koperberg suite of the Natal–Namaqua belt of South Africa (1029 ± 10 Ma, Clifford *et al.* 1995) could be slightly younger or coeval.

Rodinia reconstructions. Figure 4 shows a partial reconstruction of Rodinia at the end of the Mesoproterozoic based on the AUSMEX (Australia–Mexico) hypothesis (Wingate *et al.* 2002) and other recent continental correlations (Loewy *et al.* 2003, and references therein). The locations of significant Grenvillian massif-type anorthosites are also shown after Ashwal (1993), Clifford *et al.* (1995) and Keppie *et al.* (2003). Three possible origins for the Argentine anorthosites are indicated. The first ((1) in Fig. 4) implies Laurentian derivation as part of the basement of the exotic Precordillera terrane, with the present-day occurrence of anorthosites in the Western Sierras Pampeanas purely a consequence of the early Palaeozoic accretion of the allochthon to the proto-Andean margin of Gondwana. However, we consider an autochthonous or para-autochthonous origin within Gondwana just as likely, either SW of the Amazonian craton (2) or at the tip of the Arequipa–Antofalla block (3), according to the probable palaeogeographical positions of these continental masses outboard of the eastern margin of Laurentia (Loewy *et al.* 2003). All three alternatives are compatible with the view that the Western Sierras Pampeanas Grenvillian basement was once part of a continuous Grenvillian belt. Moreover, it can be envisaged from Figure 4 that the Appalachian, Argentine, Oaxaquia and Natal–Namaqua anorthosites might represent a late Mesoproterozoic (1.0–1.1 Ga) regional anorthosite-forming event centred between the Amazonia, Kalahari–Natal–Namaqua, and Laurentia–Australia cratons. In either of the autochthonous or para-autochthonous origins, this basement would have represented part of the Grenvillian belt that eventually became incorporated into Gondwana, before (perhaps long before) the arrival of the Precordillera terrane. More precise geochronology would be required to test whether the anorthosite magmatism could be synchronous (and perhaps cogenetic) with the intraplate mafic large igneous province recognized by Hanson *et al.* (2004) as developing 1106–1122 Ma ago between the Kalahari craton and Laurentia.

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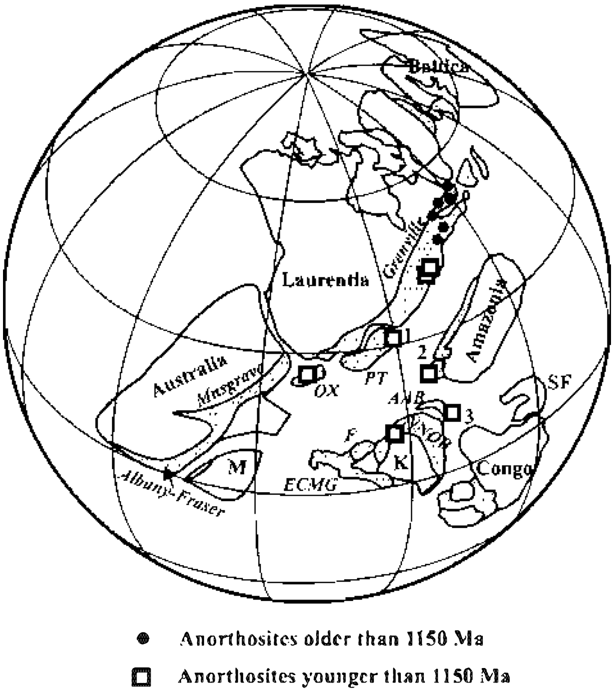

Fig. 4. Partial reconstruction of Rodinia by the end of the Mesoproterozoic with Laurentia in its present-day position (see text for sources). Grenvillian belt (stippled): AAB, Arequipa Antofalla block; ECMG, Ellsworth, Coats Land, Maudheim and Grunehogna provinces (West Antarctica); F, Falkland (Malvinas); NNOB, Natal Namaqua orogenic belt; OX, Oaxaquia terrane; PT, Precordillera terrane. Pre-Grenvillian cratons (grey): K, Kalahari; M, Mawson block of East Antarctica; SF, San Francisco. Symbols show location of massif-type anorthosites. 1, 2 and 3 are alternative hypothetical positions of the Argentine anorthosite massifs.

Note added in proof

Fieldwork in November 2004 has revealed that the third body, inferred from LANDSAT imagery, is not in fact anorthosite. The other two are confirmed.

References

ACEÑOLAZA, F.G
evolution in western South America—a discussion. *Tectonophysics*, **354**, 121–137.

ALEINIKOFF, J.N., WRIGHT HORTON, J.
Proterozoic age for the Montpellier Anorthosite, Goochland terrane, eastern Piedmont, Virginia.

ASHWAL, L.D.

ASHWAL, L.D. & SEIFERT, K.E. 1980. Rare earth element geochemistry of anorthosite and related rocks from the Adirondacks, N.Y. and other massif-type complexes, N.Y. and other massif-type complexes. *Geological Society of America Bulletin*, **91**, 105–107.

CASQUET, C., BALDO, E.,
FANNING, C.M. & SAAVEDRA, J. 2001. Involvement of the Argentine Precordillera Terrane in the Famatinian mobile belt: geochronological (U–Pb SHRIMP) and metamorphic evidence from the Sierra de Pie de Palo. *Geology*, **29**, 703–706.

CLIFFORD, T.N., BARTON, E.S.,
A crustal progenitor for the intrusive anorthosite–charnockite kindred of the cupriferous Koperberg Suite, Namaqualand, South Africa. New isotope data for the county rocks and the intrusives. *Journal of Petrology*, **36**, 231–258.

COTKIN, S.J.
meta-anorthosite and related jotunites, Western Gneiss region, Norway. *Lithos*, **40**, 1–30.

DALZIEL, I.W.D. 1997. Neoproterozoic–Paleozoic geography and tectonics: review, hypothesis, environmental speculation. *Geological Society of America Bulletin*, **109**, 16–42.

DOIG, R. 1991. U–Pb zircon dates of Morin anorthosite suite rocks, Grenville province, Quebec. *Journal of Geology*, **99**, 729–738.

GALINDO, C., CASQUET, C., RAPELA, C., PANKHURST, R.J., BALDO, E. SAAVEDRA, J.
Precambrian and Lower Paleozoic carbonate sequences from the Western Sierras Pampeanas of Argentina: tectonic implications. *Precambrian Research*, **131**, 55–71.

HANSON, R.E., CROWLEY, J.L. & BOWRING, S.A. ET AL. 2004. Coeval large-scale magmatism in the Kalahari and Laurentian cratons during Rodinia assembly. *Science*, **304**, 1126–1129.

HERZ, N. & FORCE, E.R. 1984. *Rock Suites in Grenvillian Terrane of the Roseland District*,
America, Special Papers, **194**, 187–214.

KEPPIE, J.D.,
LOPEZ, R. 2003. Geochronology and geochemistry of Grenvillian igneous suites in the northern Oaxacan Complex, southern Mexico: tectonic implications. *Precambrian Research*, **120**, 365–389.

LOEWY, S.L.,
Laurentia in Rodinia: constraints from whole-rock Pb and U/Pb
ogy. *Tectonophysics*, **375**, 169–197.

LUCASSEN, F.
Palaeozoic U–Pb formation ages of titanite indicate long-standing high-*T* conditions at the western margin of Gondwana (Argentina, 26–29°S). *Journal of Metamorphic Geology*, **21**, 649–662.

MCLELLAND, J.,
of oxide-, apatite-rich gabbronorites associated with Proterozoic massif anorthosites: examples from the Adirondacks Mountains, New York. *Contributions to Mineralogy and Petrology*, **116**, 225–238.

MCLELLAND, J.M.
ment age of anorthositic rocks of the Marcy massif, Adirondack Mts., New York. *Journal of Geology*, **98**, 19–41.

OWENS, B.E. & DYMEK, R.F. 1992. Fe–Ti–P rocks and massif anorthosite: problems of interpretation illustrated from the Labrieville and St-Urbain plutons, Quebec. *Canadian Mineralogist*, **30**, 163–190.

OWENS, B.E. & SAMSON, S.D.
history of the Goochland terrane, easternmost Grenville crust in the southern Appalachians. *Geological Society of America*,
33, 28.

PANKHURST, R.J. & RAPELA, C.W. 1998. Introduction. *In*: PANKHURST, R.J. & RAPELA, C.W. (eds) *The Proto-Andean Margin of Gondwana*. Geological Societ, London, Special Publications, **142**, 1–9.

PETTINGILL, H.S.,
anorthosites, charnockites, and granulites in the Central Virginia Blue Ridge: Nd and Sr isotopic evidence. *Contributions to Mineralogy and Petrology*, **85**, 279–291.

RAMOS, V.A., DALLMEYER, R.D. & VUJOVICH, G.I. JR.
Early Palaeozoic docking of the Precordillera, central Argentina. *In*: PANKHURST, R.J. & RAPELA, C.W. *Geological Society of America Bulletin*, 11, 1481–1491. *Gondwana*. Geological Society, London, Special Publications, **142**, 143–158.

THOMAS, W.A. & ASTINI, R.A. 1996. The Argentine Precordillera: a traveler from the Ouachita embayment of North America Laurentia. *Science*, **273**, 752–757.

WIEBE, R.A. 1980. Anorthositic magmas and the origin of Proterozoic anorthosite massifs. *Nature*, **286**, 564–567.

WINGATE, M.T.D PANKHURST, R.J., RAPELA, C.W., GALINDO, C
between Australia and Laurentia: no SWEAT, no AUSWUS? *Terra Nova*, **14**, 121–128.