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Basement evolution of the Sierra de la Ventana Fold Belt: new evidence for Cambrian continental rifting along the southern margin of Gondwana

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Abstract: U–Pb sensitive high-resolution ion microprobe data together with geochemical and Nd isotope analyses obtained in the basement complex of the Sierra de la Ventana Fold Belt indicate that the Early Palaeozoic passive margin history of the basin followed Cambrian magmatism related to rifting in a 600 Ma Neoproterozoic crust. The Cambrian episode started with intrusion of 531 ± 4 and 524 ± 5 Ma A- and I-type granites derived from a dehydrated infracrustal source (ϵNd_{530} −3.1 to −5.9), and culminated with eruption of high-Zr peralkaline spherulitic rhyolites derived from an undepleted lithospheric mantle (509 ± 5 Ma; ϵNd_{509} +0.5 to +1.0). These rift-related magmatic rocks were covered by shelf sediments deposited along a once-continuous passive margin, encompassing the Sierra de la Ventana Fold Belt, the Cape Fold Belt, the Falkland/Malvinas microplate and the Ellsworth Mountains block in Antarctica. The Cambrian rifting event defined the outline shape of the southern part of Gondwana, and can be regarded as the initiation of the supercontinent stage, which lasted until Jurassic break-up. The conjugate continental fragments separated from Gondwana during the Cambrian rifting could be the source for microcontinents with *c*. 1000 Ma basement rocks that collided with the proto-Andean margin during Ordovician–Silurian times.

Keywords: U–Pb SHRIMP, Gondwana, geochronology, granites, rifting.

The mountain chain of the Sierra de la Ventana (also known as the Sierras Australes of Buenos Aires) represents a curved fold and thrust belt, 160 km long, located at 38°00′S, near the Atlantic margin of South America (Fig. 1). Its folded Palaeozoic sedimentary sequence has been a landmark for Gondwana reconstruction since the pioneering observations made by Keidel (1916), who established the close connection with similar sequences in South Africa, and Du Toit (1927, 1937), who included the Sierra de la Ventana and the Cape Fold Belt in his ‘Samfrau geosyncline’. Most previous studies of the Sierra de la Ventana belt have focused on the stratigraphy, sedimentology and penetrative deformation that affected the Late Cambrian? to Permian sedimentary pile (see von Gosen *et al*. (1990) and Limarino *et al*. (1999) for a comprehensive list of references on these topics). The role of the igneous–metamorphic basement of the basin in the history of Gondwana is loosely constrained because of the lack of reliable radiometric ages of the igneous rocks, partly as a result of resetting of the K–Ar and Rb–Sr systems (Varela *et al*. 1990 and references therein). These basement rocks, deformed by the penetrative Late Palaeozoic folding and shearing event(s) of the Gondwanian orogeny affecting the whole basin, are seen as the counterpart of the Saldania belt, which is the basement of the sedimentary sequence deformed in the Cape Fold Belt (Fig. 2). The Saldania belt is in turn the southernmost part of a system of Neoproterozoic–Cambrian mobile belts that welded older cratons onto the African sector during the construction of Gondwana (Fig. 2) (Rozendaal *et al*. 1999).

We have investigated the magmatic history of the basement of the sedimentary sequence deformed in the Sierra de la Ventana Fold Belt, to make direct comparison and correlation with neighbouring basement terranes in NW Argentina, Uruguay, SE Brazil, and the postulated Gondwana counterparts in South Africa and Antarctica. These rocks are geographically located in a key area for identification of (1) the processes leading to formation of the proto-Pacific margin in SW Gondwana, and (2) the Neoproterozoic collision associated with the closing of the proto-Atlantic Adamastor ocean, which amalgamated the Rio de la Plata and the Kalahari pre-Mesoproterozoic cratons (e.g. Campos Neto 2000). This study includes the first U–Pb geochronological data for the Sierra de la Ventana basement. This method is considerably less susceptible to disturbance by deformation and low-grade thermal events than those used in previous studies of this area. Precise U–Pb sensitive high-resolution ion microprobe (SHRIMP) crystallization ages, together with geochemical and Nd-isotope signatures determined for the main magmatic units of the basement, have been used to reconstruct the geological and geodynamic evolution of the area before the protracted sedimentation of the basin, which lasted almost throughout the Palaeozoic era. An important conclusion is that initiation of the long-lived marine basin was in fact closely associated with the latest igneous events registered in the Sierra de la Ventana basement and in other sectors of the proto-Pacific margin.

Geological setting

Stratigraphy and age

The Palaeozoic fold belt of the Sierra de la Ventana is surrounded by a plain underlain by Late Tertiary and Quaternary

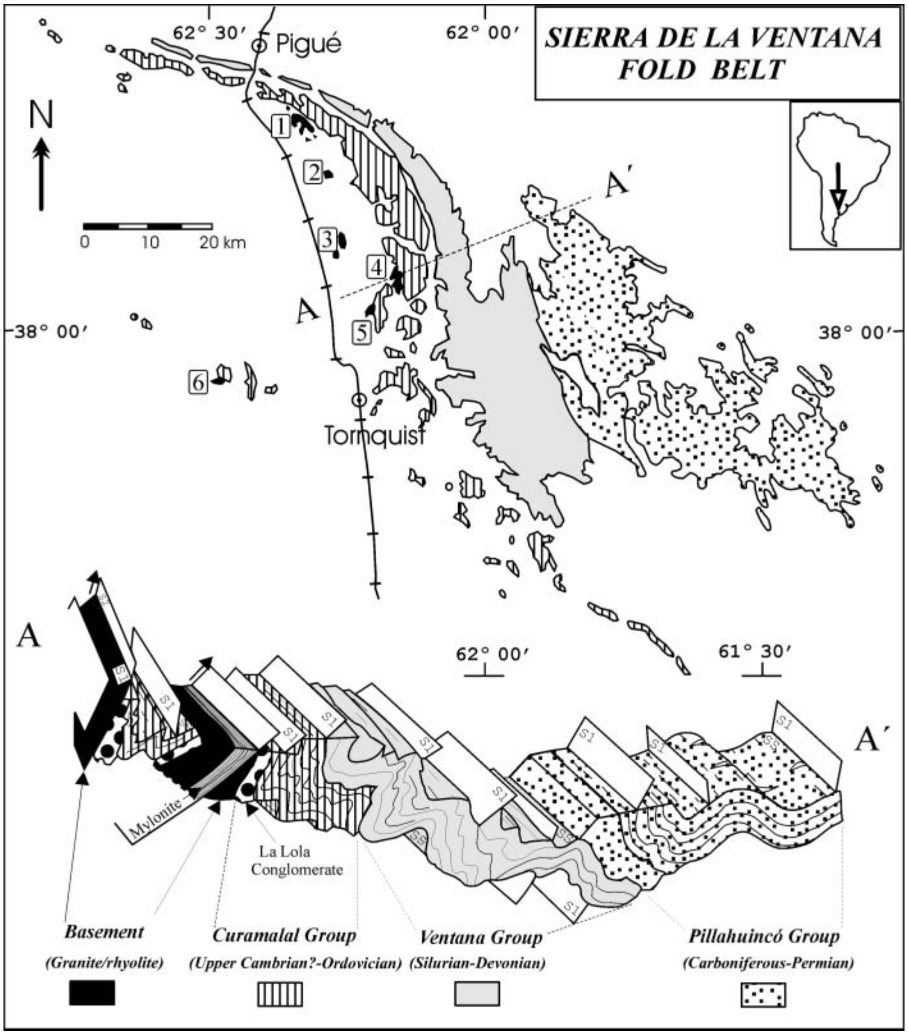


Fig. 1. Simplified geological map of the Sierra de la Ventana Fold Belt after Harrington (1947). Basement localities from Cingolani & Varela (1973): 1, La Mascota rhyolite; 2, La Ermita rhyolite; 3, Agua Blanca granite; 4, Cerro Pan de Azúcar–Cerro del Corral area; 5, San Mario granite; 6, Cerro Colorado granite. The schematic ENE–WSW cross-section (A–A′) shows the main cleavage (S_1) and shear planes (S_2) formed during Late Palaeozoic folding and thrusting of the belt (simplified, from von Gosen *et al*. 1990).

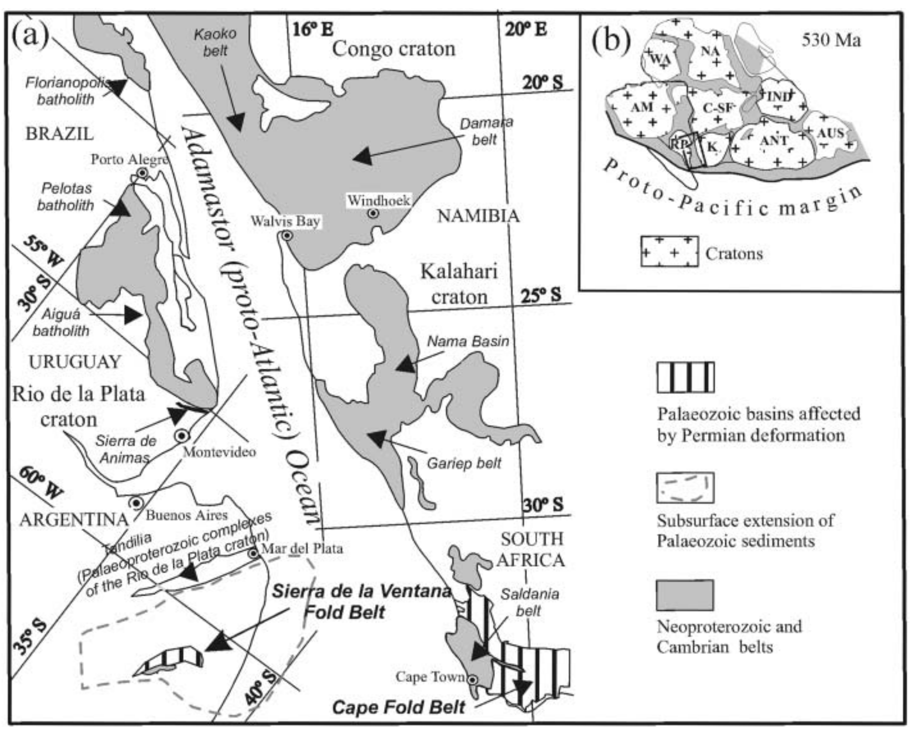


Fig. 2. (**a**) Reconstruction of SW Gondwana showing the distribution of the Neoproterozoic orogens associated with the closure of the Adamastor ocean (modified and adapted from Da Silva *et al*. 2000), and the Palaeozoic belts that resulted from the Permian Gondwanian deformation. The Neoproterozoic Florianopolis, Pelotas and Aiguá batholiths in SE Brazil and Uruguay are part of the Dom Feliciano belt (Basei *et al*. 2000). The subsurface extension of the Palaeozoic sediments of the Sierra de la Ventana belt is from Kostadinoff (1993). (**b**) Schematic reconstruction of Gondwana at 530 Ma, showing the large cratons (RP, Rio de la Plata; AM, Amazon; WA, West African; NA, North African; C-SF, Congo–São Francisco; IND, Indian; AUS, Australia; ANT, Antarctic; K, Kalahari). These are welded along Neoproterozoic mobile belts (modified after Cawood & Leitch 2001). A rectangle shows the position of the more detailed map of SW Gondwana depicted in (**a**).

sediments. Geophysical data (gravity, magnetism, heat flux and refraction seismicity; Kostadinoff 1993), as well as information from boreholes, show that the folded Palaeozoic sediments form a large subsurface basin, extending eastwards as far as the Middle Proterozoic Tandilia belt, and reaching a maximum thickness of 9 km, with the widest sector extending towards the Atlantic Ocean (Fig. 2).

The rocks of the Sierra de la Ventana Fold Belt consist of (1) a thick Palaeozoic sedimentary pile that constitutes most of the belt, and (2) a poorly exposed basement complex consisting of small outcrops (1–1.5 km^2) of acid igneous rocks located on the SW side of the orogen (Fig. 1).

The stratigraphy of the Palaeozoic sequences was described by Harrington (1947), who divided the clastic sedimentary pile into three groups, ranging in age from Late Cambrian? to Permian (Fig. 1). Siliciclastic marine sedimentary rocks of the Upper Cambrian?–Ordovician Curamalal Group (thickness *c.* 1150 m) dominate the lower part of the sequence. The coarse-grained basal clastic rocks of the Curamalal Group, known as the La Lola conglomerate (see cross-section, Fig. 1), contain pebbles of predominant quartzite and rare rhyolite. It has been assumed that the rhyolites represent the uppermost part of the basement complex (von Gosen *et al*. 1990). There are no fossils in the Curamalal Group, and its age has been assigned to the Cambrian–Silurian interval only on the basis of stratigraphic evidence (see Limarino *et al*. (1999) for references). The Devonian(?) Ventana Group (thickness *c.* 1500 m) is also dominated by marine siliciclastic sedimentary rocks. An Early Devonian age has been traditionally assigned to this group from brachiopods found in its uppermost part (Lolén Formation, Harrington 1980). However, the finding of *Skolithos* and new trace fossils in the Napostá Formation in the lower levels of the group suggests an Ordovician to Silurian age (Buggisch 1987). These mid-Palaeozoic formations are unconformably overlain by the Carboniferous–Permian Pillahuincó Group (thickness *c.* 2800 m) (Fig. 1). The sequence starts with Upper Carboniferous–Lower Permian diamictites associated with the Gondwana glaciations, followed by post-glacial marine pelites (Harrington 1980). The latter sediments are covered by pelites and sandstones carrying marine invertebrate fossils and deltaic facies with a *Glossopteris* flora, which indicates an Early Permian age (see Limarino *et al*. (1999) for references). The sedimentary sequence culminates with sandstones and pelites with increasingly continental provenance, which also contain interlayered pyroclastic levels (Iñiguez *et al*. 1988) that have been associated with the widespread Permian volcanism of northern Patagonia (Limarino *et al*. 1999).

Basement complex

The basement complex is dominated by: (1) granites (those of Cerro Colorado, Agua Blanca, Pan de Azúcar–Cerro del Corral and San Mario being the largest); (2) subordinate bodies of rhyolite that are also considered an integral part of the basement, such as those that crop out at La Mascota, La Ermita and Cerro del Corral; (3) minor occurrences of paragneiss (Fig. 1). Gravimetric and magnetic studies indicate that the Cerro Colorado granite is subcircular in shape with a diameter of 12 km, whereas the Agua Blanca granite is 5 km wide and 25 km long north–south (Schillizzi & Kostadinoff 1985). Earlier K–Ar and Rb–Sr geochronological studies have been carried out on both granitic and rhyolitic rocks of the basement (Cingolani & Varela 1973; Varela & Cingolani 1976;Varela *et al*. 1990, and references therein). A summary of these results recalculated according to new decay constants by Varela *et al*. (1990) indicates a range of ages from Neoproterozoic to Devonian: 678 ± 30 Ma for the Cerro del Corral rhyolites (Rb–Sr, average of three samples assuming an initial $^{87}Sr/^{86}Sr$ ratio of 0.7090); 613 ± 30 Ma for the Pan de Azúcar porphyritic dolerite (K–Ar); 594 ± 10 Ma for the Agua Blanca and Las Lomitas granites (Rb–Sr isochron, error at 1σ); 487 ± 15 Ma for the Cerro Colorado granite (Rb–Sr isochron, MSWD = 20, error at 1σ); 360 ± 21 Ma for the La Mascota–La Ermita rhyolites (Rb–Sr isochron, error at 1σ). Palaeozoic ages of <500 Ma obtained in some igneous units of the basement complex are controversial for several reasons. With the exception of the thin pyroclastic beds interlayered in the youngest Permian units, there are no signs of magmatic activity in the entire sedimentary sequence. As noted above, rhyolitic pebbles occurring in the basal conglomerate of the Ordovician sedimentary sequence have been considered as derived from the local basement (H. Harrington, discussion, in Cingolani & Varela 1973). In line with this opinion, structural and metamorphic studies suggest that the post-Precambrian ages obtained in the basement rocks were produced by subsequent deformation, heating and fluid activity that partially opened the K–Ar and Rb–Sr system (von Gosen *et al*. 1990; see below).

Deformation and metamorphism

The penetrative folding and shearing event(s) that affected both the sedimentary pile and the basement have been assigned to the Mid-Permian–Triassic interval on stratigraphic grounds and by correlation with events in the Cape Fold Belt (Harrington 1947; Varela 1978; Japas 1989; von Gosen *et al*. 1990; Cobbold *et al*. 1991; Rosello *et al*. 1997). Recent palaeomagnetic studies in the younger sedimentary unit of the Pillahuincó Group suggest, however, that this unit was deposited, deformed and remagnetized during the early Permian (Tomezzoli & Vilas 1999; Tomezzoli 2001). According to von Gosen *et al*. (1990), the entire clastic cover sequence was affected by a dominant first folding event verging to the NE, accompanied by a subvertical first cleavage (S_1). In the western part of the fold belt, the basement together with the sedimentary cover is thrust north-eastwards along mylonite zones, as in the Pan de Azúcar–Cerro del Corral sector (see cross-section Fig. 1). This event was followed by reverse faulting producing imbrications towards the NE, a second phase of folding, and shear planes (S_2) striking NW–SE (von Gosen *et al*. 1990). Deformation was accompanied by anchizonal to lower greenschist-facies metamorphism ($T \geqslant c.$ 300 °C), recognized on the basis of illite crystallinity and quartz recrystallization (von Gosen *et al*. 1991).

Detailed structural and mineralogical studies have shown that where the shear planes are concentrated, the granites and rhyolites of the basement complex are converted to phyllonites, mylonites and ultra-mylonites (von Gosen *et al*. 1990; Delpino 1993). Ductile recrystallization of quartz, K-feldspar and biotite are widespread (Delpino 1993). Mylonitization of the basement rocks caused various degrees of mobilization of major and trace elements, including the REE (Grecco *et al*. 2000). Si and those elements located in the micas (Al, Cr, Rb, Ba and Cs) proved to be the least mobile at low degrees of deformation, but intense deformation promoted extreme mobility of almost all elements except Si (Grecco *et al*. 2000).

Geochemistry and tectonomagmatic affinity

Selected chemical analyses of most of the units of the basement complex are shown in Table 1. This includes data for samples

Table 1. *Selected chemical analyses of Cambrian magmatic units from Sierra de la Ventana*

	Agua Blanca granite (SLV065)	Cerro Colorado granite (SLV001)	San Mario granite (SLV007)	La Ermita rhyolite (SLV066)	La Ermita rhyolite (SLV004)	La Mascota rhyolite (M1M6)
Major oxides (wt%)						
SiO_2	75.69	76.39	72.81	77.06	76.2	75.23
TiO_2	0.04	0.07	0.26	0.12	0.12	0.18
Al_2O_3	12.79	12.82	13.7	11.42	11.38	10.7
Fe_2O_3	0.64	1.01	1.08	1.79	2.22	4.20
FeO	0.66	0.26	0.48	0.29	0.16	0.14
MnO	0.08	0.03	0.06	0.01	0.02	0.02
MgO	0.02	0.07	0.35	0.02	0.01	0.04
CaO	0.60	0.48	0.71	0.30	0.60	0.01
Na_2O	3.88	3.87	4.11	4.17	4.58	2.69
K_2O	4.46	4.96	4.55	4.02	3.52	5.72
P_2O_5	0.01	0.02	0.07	0.01	0.01	0.01
H_2O^+	0.02	0.43	0.3	0.01	0.29	0.01
H_2O^-	0.13	0.03	0.13	0.03	0.08	0.00
Total	99.02	100.44	98.61	99.25	99.19	98.95
Trace elements (ppm)						
Cs	18.9	14.1	4.8	b.d.	b.d.	b.d.
Rb	757	436	244	186	159	250
Sr	9	12	113	15	12	18
Ba	7	63	722	21	12	46
La	12.1	19.1	43.1	49.1	56.0	130
Ce	32.3	50.9	72.8	106	119	240
Pr	5.66	7.36	9.39	12.6	14.4	38.8
Nd	23.7	31.0	33.0	45.2	51.8	151
Sm	10.5	10.9	6.31	12.0	13.9	40.5
Eu	0.03	0.17	0.96	0.35	0.40	0.73
Gd	11.5	12.1	5.69	12.5	14.0	39.9
Tb	2.83	2.80	1.00	2.60	2.76	7.49
Dy	18.0	17.5	5.95	15.6	16.2	41.5
Ho	4.00	3.79	1.28	3.28	3.41	8.41
Er	13.8	11.7	4.11	9.85	10.2	24.8
Tm	2.58	1.79	0.66	1.44	1.50	3.67
Yb	17.6	10.3	4.12	7.83	8.33	20.5
Lu	2.95	1.49	0.63	1.03	1.12	2.78
U	7.08	6.49	5.23	7.83	5.76	3.82
Th	45.7	46.1	22.1	32.6	33.3	47.8
Y	149	117	40.7	95.7	103	240
Nb	66.2	37.8	24.7	148	144	210
Zr	148	137	174	737	837	1770
Hf	11.1	6.3	4.9	18.0	20.2	46.2
Ta	11.3	4.12	3.59	9.56	10.4	15.8
Ga	26	24	17	26	33	37

b.d., below detection limit.

from the Agua Blanca, Cerro Colorado and San Mario granites, and La Ermita–La Mascota rhyolites (see location in Fig. 1). As the target of this part of the study is to identify the original magmatic characteristics of the rocks, we have not included chemical analyses from basement units strongly affected by the Late Palaeozoic deformation, such as the Pan de Azúcar and Cerro del Corral granites.

Individual analyses for the three analysed granitoid units plot in most cases within the compositional fields defined by a larger dataset recently reported by Grecco *et al*. (1997), which are shown for comparison in Figures 3–6. The Cerro Colorado and the Agua Blanca granites are fluorite-bearing, homogeneous low-Ca leucomonzogranites, restricted to a high silica range of 73–77% SiO_2 (Fig. 3). The alumina saturation index (ASI; molecular $Al_2O_3/(CaO + Na_2O + K_2O)$] of the less altered samples of both units ranges from 0.9 to 1.2. Fluorite is a common accessory phase, with whole-rock fluorine contents in the range 0.82–1.37%, and hydrothermal alteration is conspicuous (Grecco & Gregori 1993). The normative compositions of representative samples SLV065 and SLV001 (Table 1) plot between the 1 and 2 kbar thermal minima of the $Q{-}Ab{-}Or{-}H_2O$ system (Johannes & Holtz 1996) and this type of feature has been used to infer a shallow emplacement level for both bodies (Grecco & Gregori 1993). Both also show high Ga/Al and FeO_t/MgO ratios, low CaO and Sr, relatively high abundance levels of high field strength elements (HFSE) such as Y, Nb, Ta, U and Th, and flat REE patterns ($(La/Yb)_n = 0.46$–1.24) with strong negative Eu anomalies ($Eu/Eu^* = 0.01$–0.045) (Figs 3–6, Table 1). The high Ga/Al and FeO_t/MgO ratios, $Zr/Nb < 10$, and the high fluorine and HFSE abundances are diagnostic of A-type granites and, generally, of acid within-plate magmatism (Pearce *et al*. 1984; Leat *et al*. 1986; Whalen *et al*. 1987; Eby 1990). The Cerro Colorado and Agua Blanca granites are compositionally very similar to each other, both units plotting well within the A-type and within-plate granite fields in the discrimination diagrams of Pearce *et al*. (1984) and Whalen *et al*. (1987) (Figs 5 and 6). They plot in the A_2 group subdivision of the A-type granites, which represents magmas derived from continental crust that has

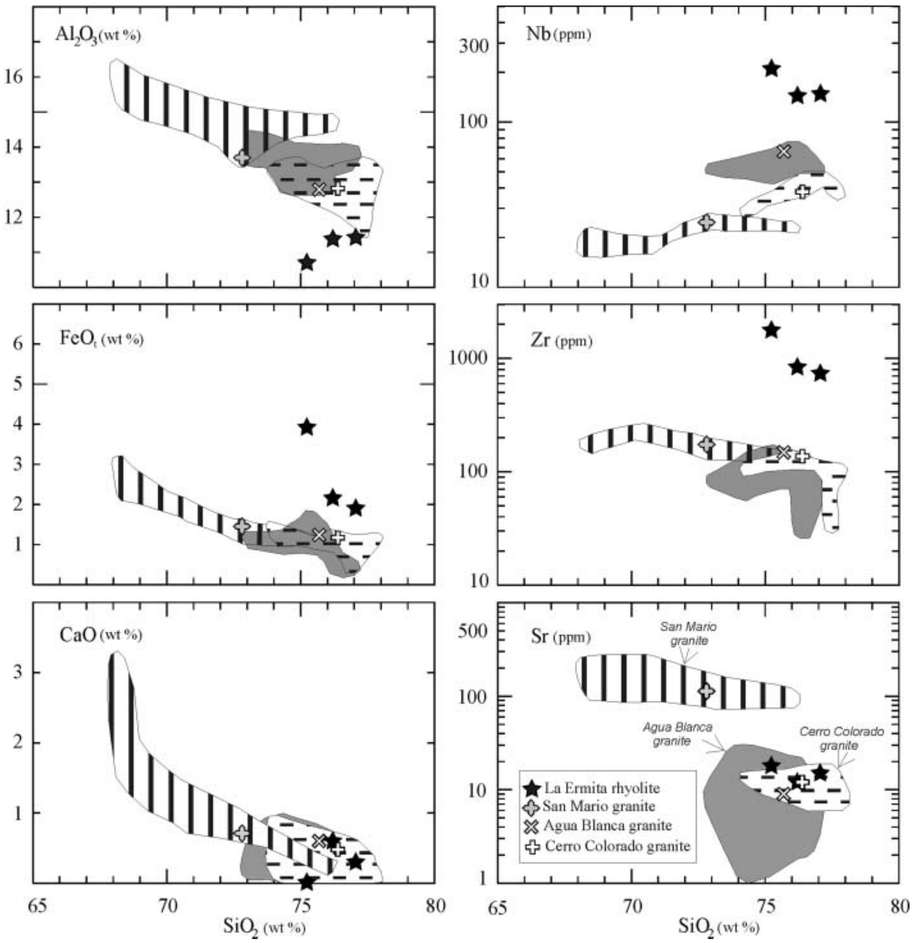


Fig. 3. Harker plots for magmatic units of the basement complex from the Sierra de la Ventana belt. Chemical analyses of selected samples from the units analysed by SHRIMP are shown in Table 1. The compositional fields for the Cerro Colorado, Agua Blanca and San Mario granites have been constructed from chemical data reported by Grecco *et al*. (1997).

been affected by continental recycling (Fig. 6) (Eby 1992). The overall geochemistry of these granites resembles that of the metaluminous to weakly peraluminous A-type granites produced by high-temperature melting of felsic infracrustal sources, rather than that of typical peralkaline complexes (e.g. King *et al*. 1997).

Compared with these granites, the coarse- to medium-grained San Mario biotite monzogranite shows a broader silica range (68–76% SiO_2), higher Al_2O_3 and Sr and a normal content of HFSE (Fig. 3, Table 1). The REE pattern of this body is steeper, with a moderate negative Eu anomaly ($(La/Yb)_n = 7.0$, $Eu/Eu^* = 0.48$) (Fig. 4). These overall are subalkaline, differentiated I-type geochemical characteristics, and they are also shown in the tectonic discrimination diagrams, where the San Mario granite plots outside the field of A-type granites (Figs 5 and 6).

The high-silica rhyolites of La Ermita and La Mascota areas (75–77% SiO_2) sometimes show a remarkably well-preserved spherulitic fabric, a typical devitrification texture that suggests rapidly quenched acid magmas. They show distinct chemical compositions, strongly enriched in HFSE, with high FeO_t/MgO ratio and are transitional to the peralkaline field using the alkali index (molecular $(Na_2O + K_2O)/Al_2O_3$ of 0.91–1.00) (Figs 3–6, Table 1). As the alkali content may reflect the effect of alteration, especially in glass-bearing rocks, high-silica rhyolites are often classified using HFSE abundances, in particular Nb and Zr (Leat *et al*. 1986). Low-Zr (<300 ppm) rocks are termed 'subalkaline', whereas high-Zr (>350 ppm) rocks are classed as 'peralkaline'. The Zr content of La Ermita–La Mascota rhyolites is very high (737–1770 ppm), indicating that these rocks were part of a peralkaline volcanic suite. It is worth noting that we were able to separate a very small amount of zircon for U–Pb SHRIMP analyses from sample SLV066, but failed to find zircon in samples with higher Zr contents (M1M6 and SLV004, Table 1). This is most probably related to the formation of alkali–zirconium–silicate complexes in peralkaline melts, inhibiting early zircon crystallization (Collins *et al*. 1982). All the analysed samples plot in the A-type fields of the discrimination diagrams (Figs 5 and 6). Within the A-type group, the rhyolites show $Y/Nb < 1.2$, which is characteristic of the A_1 group (Fig. 6); this is associated with magmas derived from similar sources to those of ocean island basalts (OIB), and emplaced in continental rifts or during intraplate magmatism (Eby 1992).

The peralkaline rhyolites of La Ermita–La Mascota areas are enriched in total rare earth elements (REE_t 278–746), with $(La/Yb)_n$ of 4.2–4.5 and Eu/Eu^* of 0.055–0.087 (Fig. 4). Although less evolved volcanic rocks are not observed in the basement complex, extreme feldspar fractionation seems to have occurred in the peralkaline rhyolites to develop the large negative Eu anomaly. Coeval peralkaline granites in the Saldania belt of South Africa (Fig. 1; see below) are associated with syenites and quartz syenites (Da Silva *et al*. 2000), suggesting that consanguineous undersaturated magma could have been related at depth to the peralkaline rhyolites. The shape of the REE patterns of rhyolites from La Ermita and La Mascota areas are identical, but the latter show higher REE_t, Zr, Y, $FeO_t + MgO$ and slightly lower SiO_2 (Table 1). It is considered that these rhyolite outcrops, separated by 10 km (Fig. 1), belong to the same peralkaline volcanic event, either related to each other by fractional crystallization, or formed from different pulses during a single

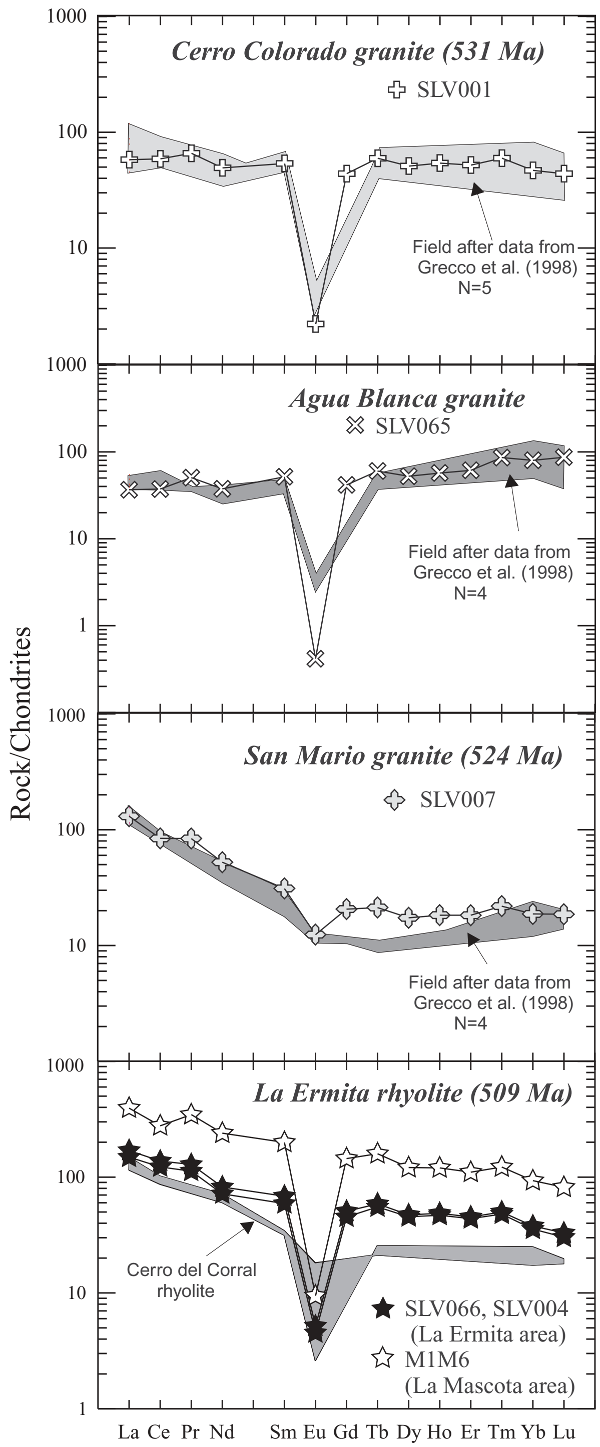


Fig. 4. Rare earth element diagrams normalized to chondrite values (Nakamura 1974) for selected samples from magmatic units of the Sierra de la Ventana basement complex (Table 1).

eruptive period. These rocks will be referred to below simply as the La Ermita rhyolite, after the locality where they have been accurately dated (see below).

Rhyolites of a different type crop out in the Cerro del Corral area (Fig. 1). Where they were not strongly affected by mylonitization, these rocks show a porphyritic fabric, with 3–4 mm euhedral K-feldspar and quartz phenocrysts set in a fine-grained groundmass (Varela & Cingolani 1976). The Cerro del Corral rhyolites analysed by Grecco *et al*. (1997) have subalkaline geochemical characteristics (SiO_2 68.0–76.5%, Al_2O_3 13.1–16.5%, Zr 153–290 ppm and Nb 23–41 ppm). Compared with the La Ermita rhyolite they are enriched in Sr and strongly depleted in Zr, Nb and Hf, showing less-enriched REE patterns and weaker negative Eu anomalies (Eu/Eu* 0.06–0.6, Fig. 4). On the other hand, the overall chemical composition of the Cerro del Corral rhyolites resembles many of the major and trace element characteristics of the San Mario granite. Based on geological evidence and whole-rock Rb and Sr contents, Cingolani & Varela (1976) inferred that the rhyolites of La Ermita–La Mascota and the rhyolites of Cerro del Corral belong to different igneous events, which is consistent with the geochemical results presented in this study. Because of similarities in petrography and Rb and Sr contents, those workers also suggested that the deformed rhyolitic pebbles in the basal conglomerate of the Palaeozoic sedimentary pile were derived from the La Ermita rhyolite.

U–Pb geochronology

U–Pb dating was carried out using a sensitive high-resolution ion microprobe (SHRIMP II) at The Australian National University, Canberra, following the procedures of Williams (1998). Zircons were hand-picked from mineral concentrates, mounted in epoxy resin together with chips of a reference zircon (AS-3), and polished. Cathodoluminescence images were used to target the magmatic rims and tips of euhedral grains. Analysis spots, mostly within the well-zoned ends of grains, were chosen to avoid cracks and inclusions. Data for the SHRIMP analyses were processed using SQUID (Ludwig 2001) and Isoplot/Ex (Ludwig 1999), and ages were calculated from the $^{206}Pb/^{238}U$ ratios after correction for the appropriate composition of common Pb, based on the measured ^{207}Pb. Analytical data can be obtained from the Society Library or the British Library Document Supply Centre, Boston Spa, Wetherby, West Yorkshire LS23 7BQ, UK as Supplementary Publication No. SUP. 18185 (3 pages). They are also available online at http://www.geolsoc.org.uk/SUP18185. Errors on the final ages are reported as 95% confidence limits.

All granitic and rhyolitic samples from the basement complex analysed in this work exhibit, to differing degrees, the physical effects of the Late Palaeozoic deformation (von Gosen *et al*. 1990). This includes kinked and broken plagioclase, K-feldspar and muscovite replaced by sericite along S_1 planes, epidote-filled extension veins and lattice deformation of quartz visible as undulose extinction, followed by recrystallization along grain boundaries. Sampling was carried out in the least deformed sectors of the various units, where the original fabric and mineralogy of the igneous units are well preserved. An exception is the strongly deformed Cerro del Corral area (Fig. 1), where the local granitic and rhyolitic rocks have a mylonitic texture, with recrystallization of quartz resulting in a fine-grained matrix along relict crystals, and newly formed sericite and albite.

Samples were analysed from the La Ermita rhyolite, and the San Mario, Cerro Colorado and Cerro del Corral granites, and the results are shown in Tera–Wasserburg diagrams (Fig. 7). Sixteen grains of the Cerro del Corral granite were analysed, and 15 of them define a precise Neoproterozoic age of 607.0 ± 5.3 Ma (Fig. 7a). A grain with an older age and a large error (reflecting inheritance?) was not used for the age calculation. From the 16 analysed grains of the Cerro Colorado granite, two show Neoproterozoic inheritance at 640 and 710 Ma (Fig. 7b); the remaining 14 grains define an Early Cambrian age of

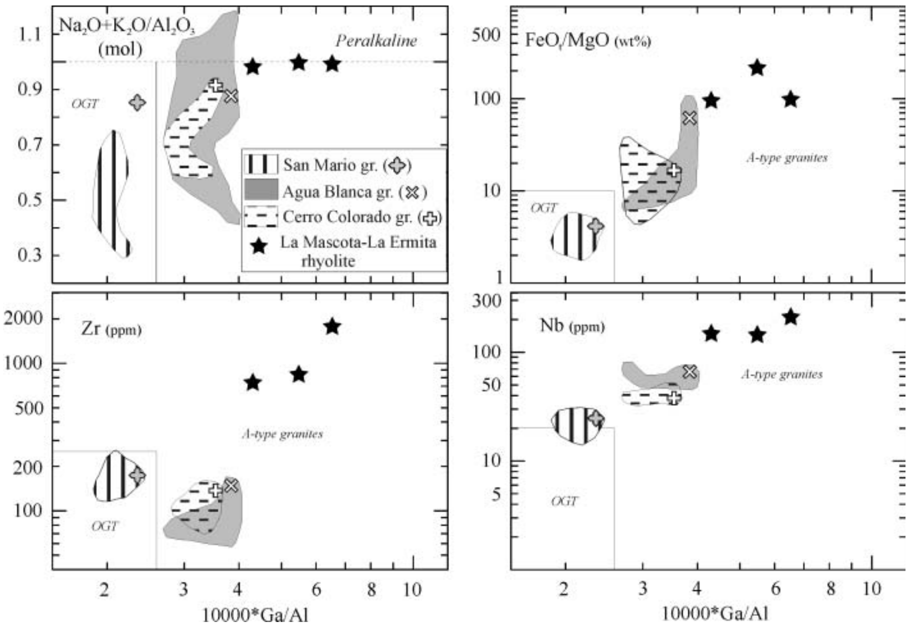


Fig. 5. Distribution of magmatic units from the Sierra de la Ventana belt on Zr, Nb, $(Na_2O + K_2O)/Al_2O_3$ (mol) and FeO_t/MgO v. $10\,000 \times Ga/Al$ A-type classification diagrams of Whalen *et al*. (1987). OGT, other granitic types. The compositional fields for the Cerro Colorado, Agua Blanca and San Mario granites have been constructed from chemical data reported by Grecco *et al*. (1997).

531.1 ± 4.1 Ma. Potentially inherited zircon cores of the same sample (SLV001), analysed using the less precise SHRIMP I ion microprobe, produced ages similar to the rims. Twelve grains of the San Mario granite also gave an Early Cambrian age of 524.3 ± 5.3 Ma, with inheritance at 550–580 Ma and Pb loss (one grain) at 495 Ma (Fig. 7c). It was not possible to separate zircon from samples of the Agua Blanca granite; for the purpose of this paper it is assumed that this has the same age as the fluorite-bearing Cerro Colorado granite, with which it shares many geochemical characteristics (see above). Finally, 19 weakly zoned zircons from a sample of the La Ermita rhyolite produced a Mid-Cambrian age of 509.0 ± 5.3 Ma (Fig. 7d).

Nd isotope data

Both Nd and Sr isotope ratios were determined on nine selected samples of the La Ermita rhyolite and the Cerro del Corral, Cerro Colorado, Agua Blanca and San Mario granites (Table 2). Strong deformation during the Late Palaeozoic low-grade event produced Rb and Sr mobility in various lithologies of the basement complex (Grecco *et al*. 2000). This is confirmed by the meaningless initial $^{87}Sr/^{86}Sr$ ratios (not reported here) calculated for several samples using the determined U–Pb ages. On the other hand, the REE patterns of the various units show very little scatter (Fig. 4) and are consistent with the geochemical signature displayed by other less mobile elements such as Zr, Y, Nb and Ga. Thus, the original isotope signature of the magmatic rocks has been inferred only from Nd isotope data (Table 2, Fig. 8).

The ϵNd_t values for magmatic rocks from the Sierra de la Ventana basement show a noticeable decrease with crystallization age (Fig. 8). Model ages for mantle derivation of a crustal source of the magmas (T_{DM}*, using the model of DePaolo *et al*. (1991)) show a reverse trend with crystallization ages, increasing from *c*.1200 Ma for La Ermita rhyolite to *c*.2000 Ma for the Neoproterozoic Cerro del Corral granite (Fig. 8). Altogether the Nd isotope data suggest that there were three distinct magmatic pulses derived from different sources, and that the 'mantle component' in these sources increases with decreasing intrusion age. An ϵNd_{607} value of −9.2 for the Cerro del Corral granite suggests an important *c*. 2000 Ma Palaeoproterozoic crustal component in the source of this granite. As the Palaeoproterozoic metamorphic complexes of the Tandilia belt crop out along the northern edge of the Palaeozoic basin of Sierra de la Ventana (Fig. 2), reworking of these complexes is the likely origin of the Cerro del Corral granite (see below).

Regardless of the different geochemical characteristics found in the Cambrian granite suite, namely, the A-type affinity for the Cerro Colorado and Agua Blanca granites compared with the calcalkaline characteristics of the San Mario granite, the three bodies show a restricted range of ϵNd_{530} between −3.1 and −5.9. The roughly coeval Cape Granite Suite in South Africa shows slightly higher ϵNd_t values, between –2.0 and –2.7 (Fig. 8, data from Da Silva *et al*. (2000) recalculated using $^{143}Nd/^{144}Nd$ of 0.512638 and $^{147}Sm/^{144}Nd$ of 0.1966 for the Chondritic Uniform Reservoir). This isotopic signature could be explained either by direct derivation from an infracrustal Mesoproterozoic and older source, or by contamination of mantle-derived magmas with an older crustal component, such as either the Neoproterozoic granites or the country rock metasediments. As the intrusion of the A- and I-type granites was preceded by a 600 Ma anatectic event, derivation of the early Cambrian granite suite from an infracrustal source that was dehydrated by a previous melting episode is the preferred hypothesis. The lack of coeval mantle-derived magmas, and the geochemical affinity with the A_2 group that is usually associated with crustal recycling, are also consistent with this origin.

The initial Nd isotope value of the La Ermita rhyolite is close to the Bulk Earth model reservoir at the time of crystallization (mean ϵNd_{509} +0.5, T_{DM}* 1200 Ma, Fig. 8). This suggests that the peralkaline volcanic magma was derived from a lithospheric mantle source that had not been previously depleted in incompatible elements.

Discussion

Age and geological evolution of the Sierra de la Ventana Fold Belt

A schematic geological evolution of the Sierra de la Ventana belt is shown in Figure 9, based on the new U–Pb crystallization

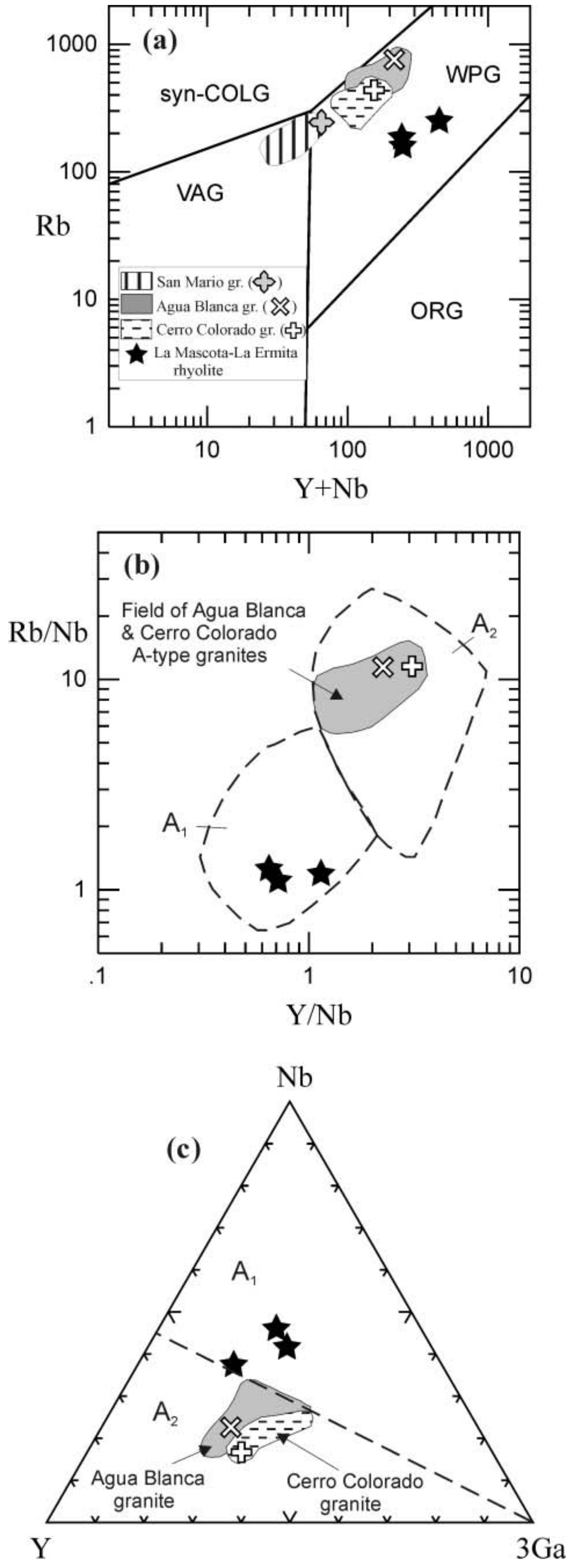


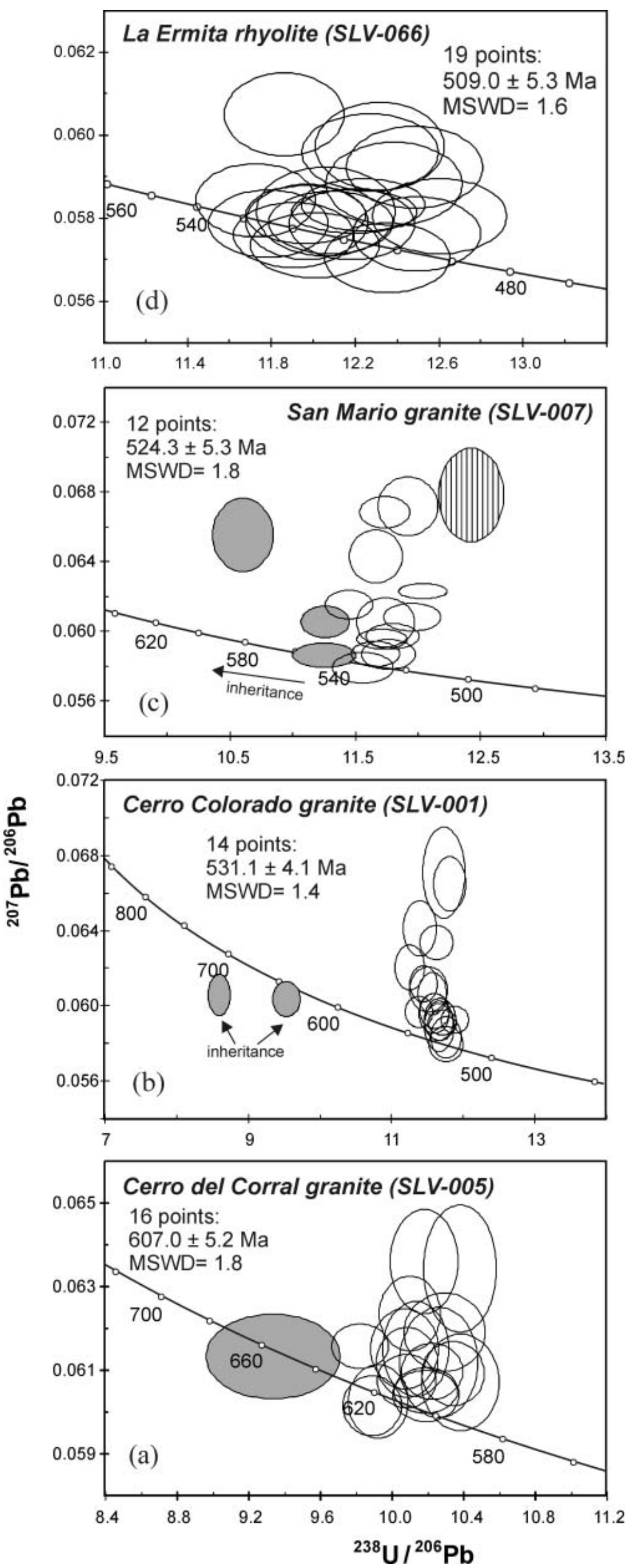
Fig. 6. (**a**) Rb v. Y + Nb discrimination diagram for within-plate granites (WPG), volcanic-arc granites (VAG), syn-collision granites (syn-COLG and ocean-ridge granites (ORG) (Pearce *et al*. 1984). (**b**) Rb/Nb v. Y/Nb and (**c**) Y–Nb–3Ga diagrams for A-type granite subdivision after Eby (1992). A_1, rift, plume- and hotspot-associated granites derived from an OIB mantle source; A_2, post-collisional, post-orogenic and anorogenic granites derived from infracrustal, igneous sources. Symbols for representative samples of the igneous units from Sierra de la Ventana as in Figure 3. The compositional fields for the Cerro Colorado, Agua Blanca and San Mario granites have been constructed from chemical data reported by Grecco *et al*. (1997).

ages and the geochemical–isotopic characteristics of the magmatic rocks. At least three distinct acid magmatic pulses are recognized in the basement complex: Neoproterozoic granites, an Early Cambrian suite and a Mid-Cambrian volcanic episode.

The magmatic history started with the intrusion of 607 ± 5 Ma crust-derived granites (ϵNd_t of -9.2) in poorly preserved paragneisses and schists of unknown age. This precise result confirms previous K–Ar and Rb–Sr studies in the Cerro Pan de Azúcar–Cerro del Corral areas reporting Neoproterozoic ages with larger errors, which were assigned to the Brasiliano–Pan African tectonomagmatic cycle (Varela & Cingolani 1976; Varela *et al*. 1990). After an interval of *c*. 80 Ma, the Neoproterozoic rocks were intruded by Early Cambrian granites (time scale of Gradstein & Ogg 1996) that volumetrically dominate the basement and are here called the Sierra de la Ventana granite suite. This suite includes the Cerro Colorado granite (531 ± 4 Ma), the Agua Blanca granite, both displaying A_2-type geochemical characteristics, as well as the San Mario granite (524 ± 5 Ma) and the Cerro del Corral rhyolite, which also has calcalkaline signatures. This is the first geochronological evidence for a Cambrian granitic event in the Sierra de la Ventana belt, and has important implications for continental correlations and the assembly of Gondwana (see below). Previous Rb–Sr studies in granites of this suite yielded either errorchrons, e.g. Cerro Colorado granite, 487 ± 15 Ma (1σ), MSWD $= 20$ (Varela *et al*. 1990), or reference errorchrons constructed from samples of more than one granitic unit, e.g. Agua Blanca–San Mario granites, 594 Ma (Cingolani & Varela 1973;Varela *et al*. 1990). Our geochemical data suggest that these last two granites are not consanguineous (e.g. their contrasting Sr contents for a given silica range, Fig. 3).

The magmatic history of the basement complex of Sierra de la Ventana belt culminated during the Mid-Cambrian with the eruption of La Ermita peralkaline rhyolite at 509 ± 5 Ma (Fig. 9). This new age is older than those obtained in previous Rb–Sr and K–Ar determinations, which include an Rb–Sr errorchron age of 360 ± 21 Ma (1σ) obtained in the La Mascota and La Ermita areas (Cingolani & Varela 1973;Varela *et al*. 1990), a single Rb–Sr model age of 388 Ma for a rhyolitic boulder of La Lola conglomerate (Varela & Cingolani 1976) and whole-rock K–Ar ages of 249 ± 8 Ma and 221 ± 6 Ma reported for two samples from La Mascota rhyolites (Varela & Cingolani 1976). The new Mid-Cambrian age determined for La Ermita rhyolite, if extended to the geochemically similar rhyolitic boulders found in the basal conglomerate of the sedimentary sequence, solves a longstanding controversy on the age of these rocks. U–Pb SHRIMP data presented in this study show that all igneous units recognized in the basement complex, including the rhyolites, are constrained to the Neoproterozoic–Mid-Cambrian interval. Post-500 Ma ages obtained in various units of the basement by K–Ar and Rb–Sr methods were probably rejuvenated during the Late Palaeozoic folding and shearing of the orogen. The age of La Ermita rhyolite is regarded as an older age limit for the base of the Palaeozoic sedimentary pile (Curamalal Group), as there is no evidence of coeval volcanism, only rhyolite pebbles, in the lowermost unit (La Lola conglomerate, Fig. 1).

Geological relations indicate that the 509 Ma La Ermita rhyolites were erupted over the Agua Blanca granite, of which subsurface bodies have been recognized gravimetrically (Schillizzi & Kostadinoff 1985). Assuming that removal of 5–8 km of overburden was required to expose the coarse-grained Early Cambrian granites, exhumation must have occurred at a relatively high rate, i.e. about 0.2–0.5 mm a^{-1}. The 2150 m of marine siliciclastic sediments of the Late Cambrian?–Devonian Curamalal and Ventana groups that overlie the Middle Cambrian peralkaline rhyolites were deposited in a gently subsiding, long-lived marine basin that Harrington (1970) considered as an aulacogen. In a plate-tectonic scenario, aulagogenic basins are those located at re-entrants on continental plate margins, and their initial formation is coeval with continental break-up (Burke 1977). Assuming that La Ermita rhyolite was produced in a continental rift setting that started in the Early Cambrian with the intrusion of A_2-type granites (see below), the Lower and Middle Palaeozoic sediments of the Sierra de la Ventana belt could represent passive margin deposits formed after the rift-to-drift transition (Fig. 9). More detailed geological studies and detrital zircon analyses of the Curamalal Group are needed to evaluate whether the lowermost part of this group may have formed contemporaneously with the rift-related magmatism.



Cambrian rifting of the supercontinent

A schematic reconstruction of the proto-Pacific margin of SW Gondwana during Mid-Cambrian times is shown in Figure 10. This reconstruction required: (1) removing from the Andean margin the Late Ordovician accreted Precordillera microcontinent and other smaller terranes with Grenvillian basement (Astini *et al*. 1995; Ramos *et al*. 1998; Casquet *et al*. 2001, and references therein); (2) restoring to their original locations the Ellsworth and the Falkland/Malvinas displaced microplates produced during the Jurassic–Cretaceous break-up and dispersal of Gondwana (Mitchell *et al*. 1986; Taylor & Shaw 1989; Grunow *et al*. 1991; Rapela & Pankhurst 1992; Randall *et al*. 2000); (3) removing the Late Palaeozoic–Mesozoic sectors, including metamorphic sequences in western Patagonia (Duhart *et al*. 2002). Granodioritic orthogneisses recovered from a drilling in Tierra del Fuego (529 ± 7.5 Ma, Söllner *et al*. 2000) suggest that the basement of the southern tip of South America may have been also a displaced terrane associated with the Cambrian proto-Pacific margin. This reconstruction shows that most conspicuous Cambrian belts and microplates of southern South America,

Fig. 7. Tera–Wasserburg plots of SHRIMP zircon data for magmatic units of the basement complex of Sierra de la Ventana. Open ellipses are 68% confidence limits for analyses of crystal tips, uncorrected for common Pb; shaded ellipses are for inherited crystal cores, which were excluded from calculation of crystallization ages. A spot shown as a vertically patterned ellipse in the San Mario granite seems to have suffered subsequent Pb loss, and was also discounted from the age calculation for this unit.asement complex of Sierra de la Ventana. Open ellipses are 68% confidence limits for analyses of crystal tips, uncorrected for common Pb; shaded ellipses are for inherited crystal cores, which were excluded from calculation of crystallization ages. A spot shown as a vertically patterned ellipse in the San Mario granite seems to have suffered subsequent Pb loss, and was also discounted from the age calculation for this unit.

Table 2. *Whole-rock Sm–Nd data for samples from the Sierra de la Ventana basement*

Sample	Age (Ma)	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$(^{143}Nd/^{144}Nd)_i$	ϵNd_t	T_{DM}	T_{DM}*
Cerro del Corral granite									
SLV005	607	8.759	50.477	0.1049	0.511803	0.511386	−9.2	1670	1974
Cerro Colorado granite									
SLV001	531	11.696	33.165	0.2132	0.512536	0.511794	−3.1	8555	1488
Agua Blanca granite									
SLV003	531	11.678	30.036	0.2350	0.512496	0.511678	−5.4	−7864	1657
SLV007	531	12.665	28.527	0.2684	0.512588	0.511654	−5.9	−1734	1691
San Mario granite									
SLV007	524	6.333	33.271	0.1151	0.512155	0.511760	−4.0	1333	1547
Cerro del Coral rhyolite									
SLV006	524	8.552	25.888	0.1997	0.512307	0.511621	−6.7	5117	1744
La Ermita rhyolite									
SLV004	509	12.115	58.229	0.1258	0.512429	0.512010	0.5	1052	1181
SLV066	509	14.305	54.270	0.1594	0.512565	0.512034	1.0	1280	1141
La Mascota rhyolite									
M1M6	509	46.82	176.07	0.1608	0.512525	0.511989	0.1	1406	1214
Saldania belt granites, South Africa (Da Silva et al. *2000)*									
Dar3	547	9.03	45.94	0.1188	0.512222	0.511796	−2.7	1283	1466
Rob7	536	9.42	44.70	0.1274	0.512271	0.511824	−2.4	1320	1438
Ch36	536	2.40	17.01	0.0853	0.512147	0.511847	−2.0	1055	1402

Sm–Nd analytical procedures as described by Pankhurst & Rapela (1995). 1σ errors are *c*. 0.1% on Sm and Nd, 0.003% on $^{143}Nd/^{144}Nd$. Crystallization ages determined by U–Pb dating, except that the age of the Agua Blanca granite is assumed by analogy with San Mario.
*DM: mantle separation age (Ma) with an intermediate crustal stage (DePaolo *et al*. 1991). It is evident that these ages are more consistent and presumably more significant than the conventional model ages for direct derivation from mantle (T_{DM}).

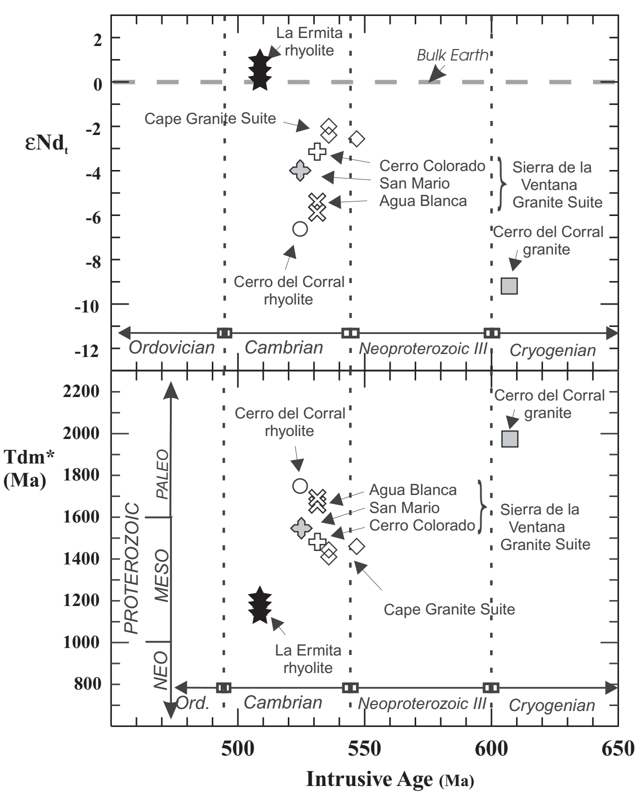


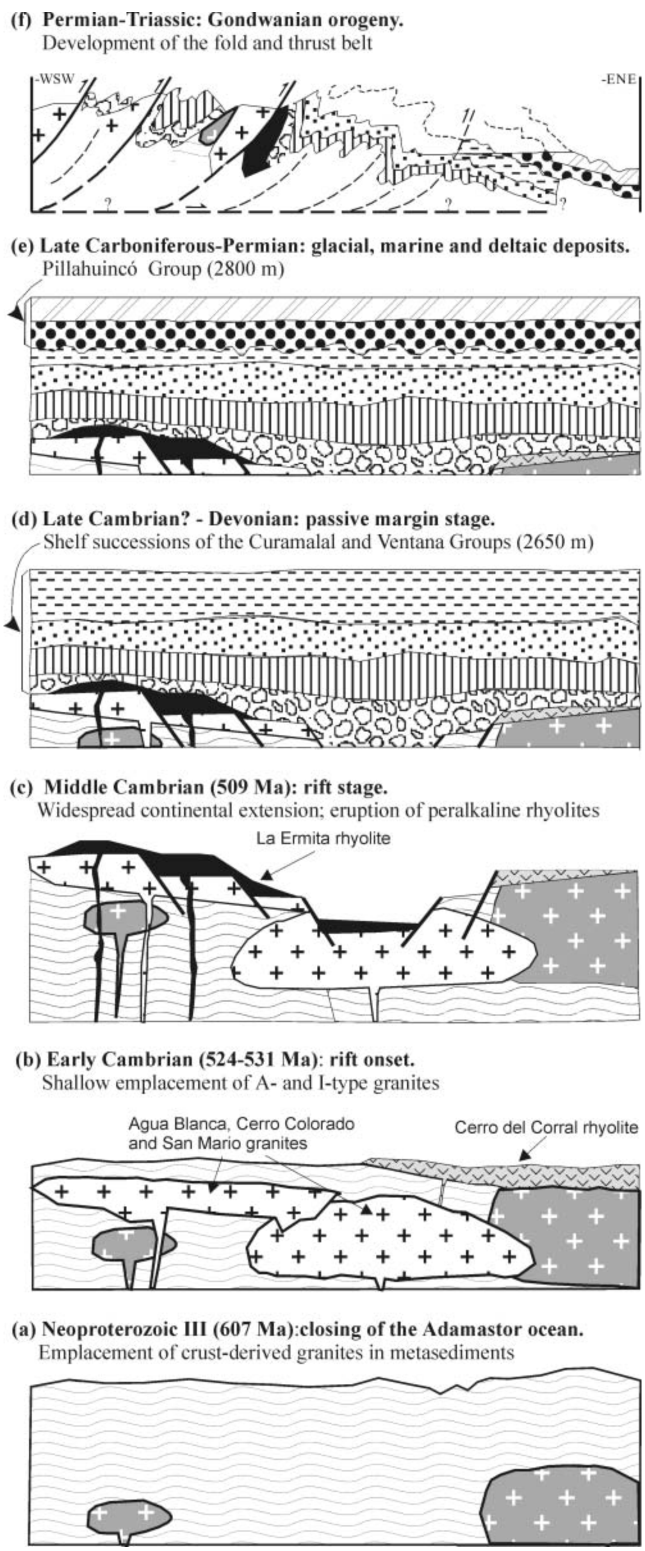
Fig. 8. ϵNd_t and crust-derived model age (T_{DM}*, using the multistage model of DePaolo *et al*. (1991)) v. crystallization age for Neoproterozoic and Cambrian magmatic units from the basement complex of Sierra de la Ventana and the Cape Granite suite of the Saldania belt. Phanerozoic and Proterozoic time scales after Gradstein & Ogg (1996) and Knoll (2000), respectively. Data for the Cape Granite Suite are from Da Silva *et al*. (2000).

South Africa and Antarctica appear discontinuously along or subparallel to what is interpreted as the southern proto-Pacific margin of the Gondwana supercontinent (Fig. 10). A comparison of the Neoproterozoic and Palaeozoic events identified in relevant sectors of this margin is shown in Table 3.

The central segment of this margin, defined by the Sierra de la Ventana belt, the Cape Fold Belt, the Falkland/Malvinas microplate and the Ellsworth microplate, is represented by thick Palaeozoic sedimentary basins that have been affected only by the Permian–Triassic Gondwanian orogeny (Fig. 10, Table 3). Mid-Cambrian rifting has been documented in the Ellsworth Mountains and the Cape Fold Belt. The protracted Late Cambrian–Devonian period of gentle subsidence has been interpreted as thermal subsidence of an early Palaeozoic passive margin produced after the rift-to-drift transition (Barnett *et al*. 1997; Curtis *et al*. 1999). On the other hand, at the western end of this large central segment, the proto-Andean belts (27–37°S, present co-ordinates) display a complex tectonic history that involved Early Cambrian and Ordovician convergent orogenies (Pampean and Famatinian), culminating in terrane collision during Late Ordovician–Silurian times (Table 3). Similarly, the Transantarctic Mountains, located at the eastern end of the central sector, underwent deformation events during the Late Precambrian–Early Cambrian (Beardmore orogeny) and the Late Cambrian–Early Ordovician (Ross orogeny) (Storey *et al*. 1996). The Ross orogeny closely matches the Famatinian orogeny, except for the accretion of Grenvillian terranes that followed the latter.

The closest sector to the Sierra de la Ventana belt is that of the Saldania and Cape Fold Belts in South Africa (Figs 2 and 10). Apart from the well-established similarities between the post-Cambrian geology, the Cambrian magmatic events identified in South Africa are also represented in the basement of the South American counterpart of the Cape Fold Belt. The Cape Granite Suite is slightly older (536–547 Ma, Armstrong *et al*. 1998; Da Silva *et al*. 2000) than the Sierra de la Ventana Granite Suite (524–531 Ma) but has similar Mesoproterozoic Nd model ages

(Fig. 8). Geochemically, the San Mario granite of Sierra de la Ventana (524 ± 5 Ma) is very similar to the Phase II, Ia association of the Cape Fold Belt (520–540 Ma, Da Silva *et al.* 2000). However, the early Cambrian Cerro Colorado (531 ± 4 Ma) and Agua Blanca A_2-type granites do not have coeval equivalents in the Saldania belt, in which alkaline granites and syenites are restricted to the Phase III event (500–520 Ma, Da Silva *et al.* 2000). The Mid-Cambrian peralkaline La Ermita rhyolite (509 ± 5 Ma) is coeval with the Phase III alkaline event in South Africa, indicating that similar tectonomagmatic conditions, typical of those found in modern continental rifts, prevailed in both belts. Cambrian trachytes and rhyolitic rocks with alkalic affinities in the Sierra de Animas of southern Uruguay (Fig. 2) may be related to the same continental rifting event (520 ± 26 Ma, Rb–Sr, MSWD = 9.6; Bossi *et al.* 1993; recalculated with error at the 2σ level).



Farther east in the margin, volcanic rocks of Mid-Cambrian age in the Ellsworth microplate have been correlated with rift-related sedimentary rocks underlying the Table Mountain Group in South Africa, and interpreted as having been formed in a continental rift environment; mid-ocean ridge basalts (MORB) were erupted near the rift axis and lithospheric mantle melts were emplaced on the rift shoulder (Curtis *et al.* 1999). Furthermore, U–Pb ages of granite cobbles and boulders from Lower to Middle Cambrian formations in the Ellsworth Mountains fall in the range 525–532 Ma (Rees *et al.* 1998; Randall *et al.* 2000), suggesting that they may have been derived from unexposed granite bodies in the Cambrian rift flanks (Curtis 2001). Remarkably, this is the same interval of crystallization ages as reported here for the Sierra de la Ventana Granite Suite. If the A_2-type granites and peralkaline event of the Sierra de la Ventana belt are correlated with those in the contiguous Saldania belt and the Ellsworth microplate, it would imply that continental rifting affected an impressive length of more than 3000 km of the proto-Pacific margin (Fig. 10, Table 3). This event could have profound implications for the initiation of Gondwana. The age of the A_2-type granites of the Sierra de la Ventana suggests that continental extension may have started during the Early Cambrian, which is consistent with the inferred timing of rifting in the Cape Fold Belt and the Ellsworth Mountains (Barnett *et al.* 1997; Curtis *et al.* 1999). Underplating of mafic magma may have triggered a high-temperature partial melting of an already dehydrated lower crust, producing the A_2-type fluorite-bearing granites of the Sierra de la Ventana belt. The eruption of peralkaline A_1-type rhyolites derived from an undepleted lithospheric mantle source is regarded as the final event of the continental rifting. Compared with the Ellsworth Mountains, the rift-related igneous rocks of the Sierra de la Ventana lack the Mid-Cambrian MORB-like depleted basaltic rocks and any evidence of exposed oceanic lithosphere. However, strong positive magnetic anomalies between the Sierra de la Ventana and the Tandilia belt (Fig. 2) have been interpreted as due to the presence of basaltic rocks beneath the thickest part of the folded Palaeozoic sequence (Köhn *et al.* 2002). Hence the possibility cannot be discarded that some sectors of the basin were floored by a transitional thin crust, mostly composed of oceanic basalts.

Fig. 9. Schematic evolution of the basement complex of the Sierra de la Ventana belt and inferred tectonic stages for the Neoproterozoic to Permian history of the orogen. The fold and thrust structure of the belt produced during the Gondwanian orogeny is after von Gosen *et al.* (1990) (see location of the WSW–ESE cross-section in Fig. 2). A protracted and episodic magmatic history of at least 100 Ma is recognized in the basement, culminating in the Mid-Cambrian with eruption of peralkaline rhyolites during a continental rift event. The Late Cambrian?– Devonian siliciclastic succession is interpreted as formed in a failed rift aulacogenic basin that was an integral part of a subsiding passive margin segment (see Fig. 10 and Table 3).

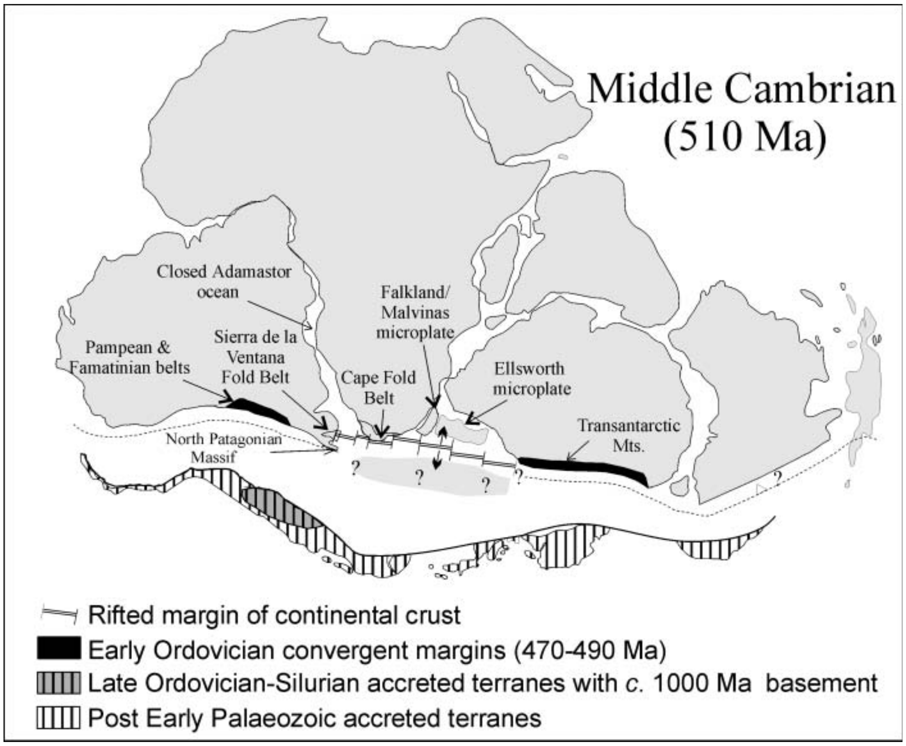


Fig. 10. Schematic palaeogeographical reconstruction of the southern margin of Gondwana during the Mid-Cambrian continental rift (adapted and modified from a Late Palaeozoic reconstruction by de Wit & Ransome 1992). Position of the Falkland/Malvinas and Ellsworth microplates after Jacobs *et al*. (1999).

Table 3. *Main Neoproterozoic and Palaeozoic events along the southwestern margin of Gondwana*

System	Time scale (Ma)	Proto-Andean mobile belts (27–37°S)	Sierra de la Ventana belt	Cape Fold Belt	Falkland/Malvinas microplate	Ellsworth microplate
	248					
Ordovician–Permian		Late Carboniferous to Permian subduction magmatism	*Gondwanian orogeny*: Permian to Triassic deformation of the Palaeozoic basins			
		Devonian (370 Ma) to Early Carboniferous intracontinental post-orogenic batholiths				
		- - - - - - - - - -				
		(b) Collision of the Precordillera Terrane (*c*. 460 Ma) (a) I-type, TTG and S-type batholiths (470–490 Ma); opening of an Early Ordovician back-arc basin	Early to Late Palaeozoic sedimentary sequences			
	495	*Famatinian orogeny (a, b)*				
Mid–Late Cambrian		Lack of subduction-related magmatism; extension in Puna and Eastern Cordillera	Peralkaline rhyolites (509 Ma)	Rift-related sedimentary sequences; alkaline granites, syenites and high-K calcalkaline series (500–520 Ma)		Late Cambrian carbonate rocks; basaltic rocks with MORB-like and lithospheric mantle signatures interlayered in Mid-Cambrian marine sediments; less common silicic rocks
	518					
Early Cambrian		(b) High-grade metamorphism, widespread anatexis, intrusion of cordierite S-type granites (522 Ma) (a) I-type metaluminous orthogneisses (530 Ma)	A- and I-type granites (524–531 Ma): Sierra de la Ventana Granite Suite	S- and I-type granites (536–547 Ma): Cape Granite Suite	Lamprophyric dykes (520 Ma)	Early(?) to Mid-Cambrian terrestrial volcaniclastic sedimentary rocks
	545	*Pampean orogeny (a, b)*				
Neoproterozoic		Passive margin Vendian to Tommotian low-grade meta-turbidites	607 Ma crust derived granites; low- to medium-grade metasediments	Low-grade metasediments of the Saldania belt	Grenvillian felsic and granitic orthogneisses (990–1135 Ma)	Grenville age igneous and metamorphic rocks

Sources: Pampean and Famatinian belts:Rapela *et al*. (1998a, 1998b), Pankhurst *et al*. (2000) and Casquet *et al*. (2001); Sierra de la Ventana belt: this paper; Saldania and Cape Fold Belts: Barnett *et al*. (1997), Armstrong *et al*. (1998), Rozendaal *et al*. (1999) and Da Silva *et al*. (2000); Falkland/Malvinas microplate: Thomas *et al*. (1998) and Jacobs *et al*. (1999); Ellsworth microplate: Curtis *et al*. (1999). Time scale: Gradstein & Ogg (1996). Ages in parenthesis are either conventional or SHRIMP U–Pb ages. TTG, tonalite–trondhjemite–granodiorite suite.

The nature and age of the crystalline basement underlying the Sierra de la Ventana–Cape Fold Belt–Falkland/Malvinas–Ellsworth segment characterized throughout by Palaeozoic sedimentary basins floored by rift-related rocks, shows contrasting differences along the margin. On one hand, the *c*. 2000 Ma Palaeoproterozoic metamorphic complexes of the Tandilia belt (in the Rio de la Plata craton) are the obvious basement underlying the northern margin of the Sierra de la Ventana belt

(Fig. 2). On the other hand, those basins that were originally located adjacent to the Grenvillian age provinces of Namaqua–Natal (southern Africa) and Heimefrontfjella (East Antarctica), i.e. the Cape Fold Belt, the Falkland/Malvinas and Ellsworth microplates, are underlain by juvenile 1000–1100 Ma rocks (Cingolani & Varela 1976; Storey *et al*. 1994; Curtis & Storey 1996; Wareham *et al*. 1998; Jacobs *et al*. 1999; Armstrong & De Wit 2002). If one or more continental fragments were rifted off from this South African–Weddell Sea sector in Cambrian times, as suggested by Curtis *et al*. (1999), it would be characterized by Grenvillian basement with a cover of Early Cambrian rift sequences and Cambrian carbonates. Such continental fragments would be potential candidates for the terranes accreted to the proto-Andean margin of South America during Late Ordovician–Silurian times (Fig. 10, Table 3). The basement of the Precordillera and Chilenia terranes are Grenville-age igneous and metamorphic rocks (Kay *et al*. 1996; Ramos & Basei 1997; Pankhurst & Rapela 1998). Grenvillian rocks from South Africa, East and West Antarctica, the Falkland/Malvinas microplate, the Grenville belt in North America and the Precordillera terrane have similar Pb, Nd and Sr isotope characteristics (Wareham *et al*. 1998). This coincidence, as well as the faunal similarities between Cambrian carbonate sequences of Laurentia and the Precordillera (Benedetto 1998, and references therein) could be explained if a region of SE Laurentia, the hypothetical Texas plateau (Dalziel 1997), rifted away from the Weddell Sea–South African sector during the break-up of the ephemeral Pannotia supercontinent (Dalziel 1997; Curtis *et al*. 1999; Curtis 2001). Aceñolaza *et al*. (2002) have also suggested that the Precordillera was a terrane originally located in a sector between South America, Africa and Antarctica, which was displaced in Vendian–Early Palaeozoic times by transcurrent, continent-parallel transcurrent faults. The results presented in this paper indicate, however, that if any such terrane originated in this sector, it would presumably have initially separated from Gondwana during the Cambrian rifting, to rejoin it later, in Late Ordovician–Silurian times. More detailed geochronological and geochemical work will be needed to further constrain the rift timing and its spatial development to refine and/or discard some of these hypotheses.

It is worth noting that the rift and passive margin stages of those sectors located at either side of the Sierra de la Ventana–Cape Fold Belt–Falkland/Malvinas–Ellsworth segment seem to have started relatively early. In the proto-Andean margin the passive margin rocks are the Late Precambrian–Early Cambrian low-grade turbidites of the Puncoviscana Formation (Durand 1996), containing 530–560 Ma detrital zircons (Lork *et al*. 1990). This margin underwent a contractional tectonic inversion, with intrusion of I-type granites (530 ± 3 Ma) followed by a late Early Cambrian (523 ± 4 Ma) high dT/dP metamorphism producing widespread migmatites formed at 6–8 kbar, S-type granites and cordieritites that have been ascribed to the collision of a parautochthonous terrane (Pampean orogeny, Rapela *et al*. 1998b, 2002), or ridge subduction under the accretionary prism (Fantini *et al*. 1998). On the other side of the Sierra de la Ventana–Ellsworth segment, Lower Cambrian siliciclastic sequences of the Transantarctic Mountains were folded, uplifted and eroded before Late Mid-Cambrian times, during compressional events previously attributed to the 'Beardmore orogeny', but more recently considered as an early stage(s) of the Ross orogeny (Rowell *et al*. 2001).

The tectonic scenario for the proto-Pacific margin arising from the above observations in the basement complex of the Sierra de la Ventana Fold Belt is one of Early to Mid-Cambrian continental rifting of the southwestern margin of Gondwana. Adjacent sectors defining the southern margin of the supercontinent, including the Cape Fold Belt, the Falkland/Malvinas microplate and the Ellsworth Mountains, also underwent coeval Early to Mid-Cambrian rifting (Curtis 2001). This extensive event produced a passive margin with associated aulacogenic basins that continued in existence until the Devonian, after which the Palaeozoic successions were folded during the Gondwanian orogeny. The Permian deformation was contemporaneous with re-initiation of subduction at the proto-Andean margin (Table 3), which is consistent with interpretations that favour a compressional back-arc setting for the Gondwanian orogeny (e.g. Trouw & De Wit 1999). In Early Ordovician times the coeval Ross and Famatinian orogenies took place at either end of the 'passive margin' segment, accompanied by voluminous silicic magmatism. In the case of the Famatinian orogeny, Early Ordovician magmatism (468–499 Ma, Pankhurst *et al*. 2000) was followed by the accretion of terranes, in part probably rifted off from the central segment underlain by juvenile *c*. 1000 Ma crystalline basement rocks.

Implications for the Neoproterozoic proto-Atlantic orogenies

The 607 Ma Cerro del Corral granite indicates that the Cambrian extensional magmatism of the Sierra de la Ventana took place in a continental crust affected by the widespread Brasiliano–Pan-African Neoproterozoic event. This is an important difference between the Sierra de la Ventana and the Saldania belt in South Africa, as the latter lacks the conspicuous *c.* 600 Ma magmatism of the Dom Feliciano belt along the coastal region of southern Brazil and Uruguay (Da Silva *et al*. 2000). A range in U–Pb emplacement ages from 633 ± 8 Ma to 571 ± 8 Ma has been recently reported for the Florianopolis, Pelotas and Aiguá granitic batholiths of the Dom Feliciano belt (see locations in Fig. 2) (Basei *et al*. 2000; Hartmann *et al*. 2002, and references therein). In southern Brazil these granites are emplaced into 2078 ± 13 Ma basement gneisses (Leite *et al*. 2000). The granitic magmatism of the Dom Feliciano belt has been related to partial closure of the proto-Atlantic Adamastor ocean between the Kalahari and the Rio de la Plata cratons (Fig. 2), with the main collisional phase at around 600 Ma (Basei *et al*. 2000; Campos Neto 2000, and references therein). Granitic rocks of this belt have ϵNd_{600} of −5.6 to −24.3, and conventional T_{DM} of 1648–3022 Ma, indicating derivation from old crustal sources, with a minor juvenile component (Da Silva *et al*. 2000). The Cerro del Corral granite, with an isotopic signature indicating a Palaeoproterozoic crustal source (ϵNd_{607} −9.2; T_{DM}* 1974 Ma, Table 2), seems to be the southernmost exposure of the magmatism associated with the Dom Feliciano belt. In this case, an obvious source is the Palaeoproterozoic rocks of the Tandilia belt, 170 km to the NE of Sierra de la Ventana (Fig. 2). The Tandilia belt, mostly composed of igneous and metamorphic rocks with U–Pb ages in the range of 2051–2228 Ma (Cingolani *et al*. 2002) and Sm–Nd T_{DM}* model ages between 2530 and 2650 Ma (Pankhurst *et al*. 2003), is the southernmost exposure of the Rio de la Plata craton.

The last Pan-African orogeny, culminating with the collision of the Congo and Kalahari cratons, occurred in the Damara belt of southern Africa (Fig. 2), and the peak regional metamorphism of this event has been dated at 511 ± 2 and 517 ± 2 Ma (Jung *et al*. 2001). Remarkably, the climax of this continental collision in southern Africa is contemporaneous with the Mid-Cambrian rifting event along the near-central segment of the proto-Pacific margin. As collision-related rifts may occur in foreland areas of collision orogens in response to indentation tectonics (Şengör 1976), a connection between the two events cannot be discounted without further studies.

Conclusions

Perhaps the most relevant conclusion arising from the study of the basement rocks of the Sierra de la Ventana belt is that the igneous history is closely associated with initiation and development of the long-lived Palaeozoic sedimentary basins. Continental rifting started in the Early Cambrian with intrusion of crust-derived metaluminous to slightly peraluminous A-type granites, and culminated in the Mid-Cambrian with eruption of peralkaline rhyolites. Lower to Middle Palaeozoic marine sediments were deposited in gently subsiding basins that were part of a long and once continuous passive margin, encompassing the Sierra de la Ventana belt, the Cape Fold Belt, the Falkland/Malvinas microplate and the Ellsworth Mountains. Shortly after the final amalgamation of the Congo, Kalahari and Rio de la Plata cratons, the Cambrian rifting event defined the outline shape of the southern part of the supercontinent. This extensive rifting episode, followed by accretion of microcontinents along the proto-Andean margin, could be regarded as the initiation of the supercontinent stage in southwestern Gondwana, which lasted until Jurassic break-up and dispersal.

A previous and distinct 600 Ma S-type granitic event is also registered in the Sierra de la Ventana basement, which is coeval with a similar granite emplacement in southern Brazil and Uruguay, associated with the closure of the Adamastor (proto-Atlantic) ocean. Therefore the Early Cambrian event affected an already dehydrated lower crust in the Sierra de la Ventana belt, which could explain the occurrence of A_2-type granites here and their absence in the Saldania belt, as the 600 Ma event is not registered in the South African sector.

The most puzzling part of the Cambrian continental rifting is that associated with the final fate of the conjugate continental sectors that were rifted along the South American–South African–Weddell Sea sector. Potential candidates for such rifted continental pieces are the microcontinents and terranes with Grenvillian basement that collided with the proto-Andean margin during the Late Ordovician and Silurian times.

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