Int Journ Earth Sciences (1999) 88:76–97

ORIGINAL PAPER

R. H. Omarini · R. J. Sureda · H.-J. Götze
A. Seilacher · F. Pflüger

Puncoviscana folded belt in northwestern Argentina: testimony of Late Proterozoic Rodinia fragmentation and pre-Gondwana collisional episodes

Received: 23 December 1997 / Accepted: 9 December 1998

Abstract Stratigraphic correlations and tectonic analysis suggest that the Puncoviscana fold belt of northwestern Argentina was an intracontinental basin with bimodal igneous suites that formed in connection with the breakup of the Rodinia supercontinent (at ~800 Ma). Several lines of evidences point to an initial lithosphere rupture, possibly induced by a rising mantle plume. The earliest synrift igneous products are represented by ultra-potassic dykes and alkaline lava flows of high LREE/HREE and low Zr/Nb–Y/Nb ratios. The dyke emplacements and the initiation of rifting were probably synchronous. They pass laterally and upwards (middle part of the Puncoviscana succession) into basalts of alkaline transitional character (OIB-like source). The distinctive chemical feature of these lavas are very similar to the source of oceanic island basalts; thus, they are thought to represent a magmatism associated with the rift and rift-drift transition stage. During this stage of rifting probably true oceanic crust was formed. The upper part of the Puncoviscana sequence, Late Precambrian/Lower Cambrian in age, comprises a thick and monotonous sequence of pillow lavas, massive basaltic flows and minor volcanic breccias and hyaloclastites. These lavas exhibit MORB trace element characteristics with high FeO_t and TiO_2, low K_2O and P_2O_5, flat light REE spectra, little or no depletion in Nb and Ta. This volcanism consists of the major and latest effusive episode from the Puncoviscana basin which was slightly modified by subduction processes. The geodynamical model proposed for the generation of these volcanic rocks could have been developed in two stages. In the first stage the volcanic event is compatible with a progressive opening of a continental rift leading to formation of a mature oceanic basin. In contrast, the second stage shows the effects of a completed Wilson cycle including a primitive volcanic arc which continued until the accreted Cuyania-Arequipa-Belen-Antofalla (CABA) terrane against the proto-Gondwana western borderland of the Amazonian shield (~535 Ma).

Key words Plate tectonics · Geochemistry · Trace fossils · Late Precambrian–Eocambrian stratigraphy and magmatism · Gravity

R. H. Omarini (✉) · R. J. Sureda
Universidad Nacional de Salta, (CONICET), Salta, Argentina

H.-J. Götze
Institut für Geologie, Geophysik und Geoinformatik,
Freie Universität Berlin, Berlin, Germany

A. Seilacher
Universität Tübingen,Tübingen, Germany

F. Pflüger · A. Seilacher
Yale University, New Haven, Connecticut, USA

Introduction

There are presently some hypothesis on the geological history and palaeogeographic connections of the Andean paleomargin of West Gondwana between 800 and 430 Ma. Since Bond et al. (1984), the possible relations of the Central Andes with Laurentia, these rift-bounded Neoproterozoic cores of Rodinia, and the correspondence with the great breakup of the ancient supercontinent are subjects of great controversy (Dalziel 1991; Hoffman 1991; Moore 1991; McKerrow et al. 1992; Unrug 1996, 1997). The palaeogeographic models proposed for these times show remarkable differences in the chronology of the great tectonic events related to continental fragmentation and drifting. Different interpretations appear for the geological development of the Altiplano-Puna, Famatina, Precordillera, Cuyo and Patagonia regions, which are considered to have had a very complex collisional Paleozoic history with allochthonous terranes on the western margin of South America (compare Ramos et al. 1984; Ramos 1988; Dalla Salda et al. 1992; Omarini and Sureda 1993, 1994; Astini et al. 1995, 1996; Wasteneys et al. 1995).

Several authors have postulated a Late Precambrian age for the Rodinia fragmentation, which starts with a pronounced crustal thinning and proto-oceanic rift-paired systems. Deep rifted asymmetrical basins are typical features of passive continental margins. Sedimentary or leptometamorphic units cover the transition between the Vendian and Tommotian times with no apparent discontinuity, offering a fairly acceptable register of trace fossils and interbedded volcanites. This model admits some Rodinian slivers which have been accreted to South America between Cambrian and Late Devonian times (Ramos et al. 1984; Omarini and Sureda 1994; Astini et al. 1995, 1996) in contrast to the continent–continent collision (Dalla Salda et al. 1992, 1993; Dalziel et al. 1994) of the extreme autochthonous to para-autochthonous viewpoint (Baldis 1989; Bonorino and Bonorino 1991; Bonorino and Llambías 1996). A key area to view this problem is the Puncoviscana belt in Northwest Argentina. The main objective of this paper is to review the geochemical and geophysical data of the Puncoviscana foldbelt in light of new petrological information and a discussion of palaeobiological and geological implications; therefore, an up-to-date review on the geodynamical development at the proto-Gondwana margin during Late Precambrian and Early Paleozoic times is also given.

Andean palaeogeographic outlines in the Neoproterozoic–Phanerozoic transition

The narrow areas of Puncoviscana outcrops form small parts of a wide surface of sedimentary basins in the South American palaeogeography. Similar registers have been found in eastern Bolivian provinces within the shelf sedimentary deposits of the Boquí, Tucavaca, Arará, Bodoquena, Itapucumi and Murciélago groups (Brockmann et al. 1972), homologous strata from the Jacadigo Group of the Corumba region, Brazil, are correlated (Almeida et al. 1976). Equivalent stratigraphic units are in the Pampean ranges (Caucete and La Clemira groups): in the Sanrafaelic-Pampean boulder, Cuyo region, with Cerro La Ventana and La Horqueta formations (Criado Roque 1972; Lucero), and the south slope of the Río de la Plata shield with Nahuel Niyeu and El Jagüelito formations (Linares and Turner 1976; Caminos 1979). The outcrops of the Puncoviscana represent an elongated intracratonic basin surrounded by land masses: from NW to SW by the Arequipa massif and its southern continuation in the metamorphic Belen-Antofalla-Cuyania belt; on the northeastern side by the Amazon shield and its peripheral elements of the Guapore massif and the Sunsas belt; and on the southeastern side by the Río de la Plata-Pampia shield.

Puncoviscana-type basins have also been recognized in other continents as a testimony of a complete breakup of the Rodinia supercontinent in the Middle Proterozoic, with North America connected to East Antarctica, after the SWEAT hypothesis (Moore 1991), or to South America in the proto-Gondwana (Dalziel 1991, 1997). Attached to these Archaean forelands with highly metamorphic Grenville belts in twin pairs, a series of narrow turbiditic and non-metamorphic basins were formed between 750 and 570 Ma, with synchronous volcanism. The southeastern edge of the Appalachian orogen is cut by the Avalon sedimentary-volcanic arc, from Newfoundland to Florida, on the current Atlantic coast of North America. The Tibbit Hill Formation (Kamo et al. 1989; Kumarapeli et al. 1988; Bevier 1989) and the Floyd Church Formation in the Albemarle Group (Seider 1978; Milton and Reinhardt 1980) are relevant units of this region, which evolved with rift processes and deep subsidence during Late Proterozoic times.

After Dalziel's (1994) hypothesis, the western North American borderland evolved and culminated in coeval development between Australia and East Antarctica in the Ross-Dallamerian belt. The Windermere Group shows very similar sedimentary deposits from Alaska to Mexico (Stewart 1972; Storey 1993). It probably had a connection in southeastern Australia with the Normanville Group of the Adelaide foldbelt and with the Beardmore, Nimrod and Byrd groups of the Transantarctic Mountains (Ross 1991; Storey et al. 1992; Goodge et al. 1993; Rowell et al. 1993). The whole fragmentation of these low-grade metamorphic basins began in the Middle Proterozoic announcing the advent and subsequent explosive evolution of metazoa. The interval encompassing the Vendian to Nemakitian transition was accompanied by wide fluctuations in sea level and the isotopic and chemical composition of seawater.

Precambrian–Eocambrian stratigraphy

The Central Andes basement in the Puna and regions of the eastern Cordillera shows a thick sedimentary sequence (mainly siliciclastic flysch-like turbidites and minor shallow-water micritic limestones, with locally thick lenses of conglomerate) known as the Puncoviscana Formation in a broad sense (Turner 1960). The major outcrops lie in several orographic units extended northwards, as a northern tract of the Pampean ranges, from the city of Tucuman to the Bolivian border (see Fig. 11). Towards the north, the rocks of the Puncoviscana Formation are gradually overlain by Paleozoic sedimentary covers. In southern Bolivia, they should be correlated with the San Cristobal Formation. Southwards from the Aconquija lineament, in the Famatinian System, some very low-grade metasedimentary strata of the Negro Peinado Formation may be correlated with the Puncoviscana belt (Aceñolaza and Toselli 1989).

During the Upper Ordovician, these basements were uplifted in the proto-Cordillera Oriental along the major compressional faults. These deep basement

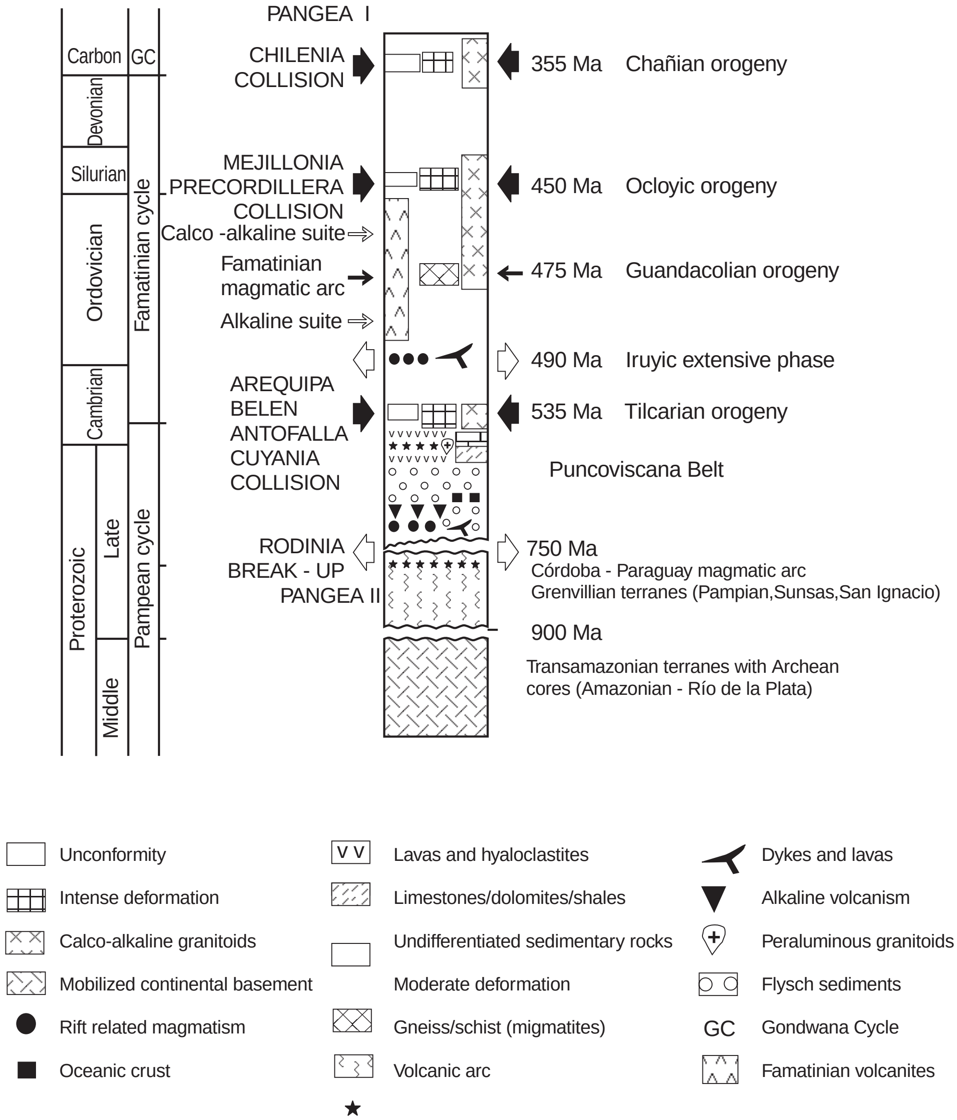


Fig. 1 Interpretive Precambrian to early Paleozoic tectono-stratigraphic column for the Pampean basement in northwestern Argentina

faults have been reactivated with morphological expression during the Andean cycle.

The epiclastic sediments largely comprise a continuous stratigraphic sequence, whose formations, lithology and tectonic environment are shown in Figs. 1 and 2 (taken from Omarini 1983 and Jêzek 1986). In these stratigraphic columns, the unit ages show palaeontological and radiometric controls on granitoid and sedimentary rocks. They suggest an evolution of Neoproterozoic continental passive margin where at least three successive episodes are distinguished:

1. A basal sequence formed mainly by immature epiclastic sedimentites (conglomerates, sandstones, arkoses and diamictites) with ultra-potassic dykes and volcanic flows interbedded. This assemblage represent an extensional tectonic rift-type setting with volcanism of mantle source signatures.
2. Marine shelf deposits of mature sandstones and extensive, very distributed limestone layers overlie the basal sequence. This lithological association, which accumulated in littoral and near-shore environments, is related to regional subsidence under stable conditions, analogous to an early stage of passive continental margin formations. The lava compositions changed from alkalic to tholeiitic becoming increasingly important as eruption age decreased.
3. The upper sequence shows the transition from the magmatic arc to a continent–continent collisional regime. The sedimentation suggests moderate water depths with prevailing siliciclastic rocks of flysch type and minor pyroclastites, hyaloclastites, volcanic layers and breccias. Some syn- and post-orogenic granites were emplaced within the Puncoviscana belt in correspondence with the Tilcaric orogeny (Early-Middle Cambrian).

Depositional setting and sedimentary record

The sedimentology of the Puncoviscana Formation has been discussed by previous authors (Omarini 1983; Omarini and Baldis 1984; Jêzek 1986, 1990). The association of sediments in the studied area can be grouped into a wide range of lithological types, based on variety in texture and internal structures, with a major setting of the following:

1. Monotonous outcrops of coarse-grained turbiditic sandstones of flysch type
2. Thick and monotonous strata of argillites, siltstones and sandstones
3. Minor massive strata of diamictites and polymictic conglomerates
4. Isolated but thick massive strata of shallow-water micritic limestones

The turbiditic sandstone association is characterized by thin to thick strata of fine- to coarse-grained sandstones, alternating with siltstones and mudstones. The vertical facies trend from heterolithics to planar laminated sandstones up into massive and pebbly sandstones and reflects a shallowing-upward progradational succession. The heterolithics represent offshore mud sedimentation interrupted by episodic influxes of storm sand forming planar and ripple lamination (in Quebrada de Escoipe, Salta). The upper surface of each storm bed was subsequently bioturbated, as indicated by a highly diverse community of trace fossils (in Los Huachos, La Quesera, Salta). The sandstones are greywackes with a flysch-like texture. Angular grains of quartz, feldspar and lithic fragments (mainly sedimentary, granitic-gneissic and scarcely volcanic in origin) are embedded in a matrix of needle-like, pale-green chlorite (in Quebrada de Lules, Sierra de Medina, Tucuman). The Tab, Tac and, more rarely, Tbc and Tbcde Bouma sequences, are the dominant style. These facies are interpreted as deposits of channels or interchannels in the sense of Mutti and Normark (1987). Intercalated with this facies, there are also non-channelized deposits with remarkable laterally continuous planar sandstone beds and with varve-like aspect (fan lobes; in Seclantas and Molinos, Salta).

The argillite–siltstone–sandstone association comprises fine-grained laminated sandstone with good grain sorting intercalated with massive or laminated argillites and silty argillites (in Quebrada Las Arcas, Salta). The argillite units are laminated (very rarely massive), usually with thin laminae of siltstones or very fine sandstone (in Niño Muerto, Salta). Rhythmic bedding is common. Many rhythmites are graded on a microscopic scale. Siltstones with convoluted lamination and scale loading are two typical sedimentary structures (in Rio Capillas, Salta).

The conglomerate facies occurs as individual normally lenticular and laterally discontinuous beds. These beds are interpreted as channel fills. The conglomerates are very immature, poorly sorted and devoid of stratification. Imbrication is rare to absent, although flow structures around large clasts may be common. This facies contains subangular to subrounded quartzite and sandstone clasts and rounded but oblate shale clasts. Most of the conglomerates have a fine-grained matrix which consists of subangular sandy grains with lithic fragments and chert. Their unstratified and disorganized nature is consistent with deposition by a mass flow mechanism (in Corralito, Las Tienditas and Molinos, Salta).

The wide outcrops with carbonate facies consist of massive non-fossiliferous limestones. The fine-grained beds of those units indicate a shallow marine environment with low sedimentation rates. Micrite represents the main lithological type of most of the units. Occurrences of intramicrite beds are relatively rare in abundance. The frequent association of bearing like algal carbonaceous micrite is inferred from the presence of very finely laminated black limestones. The mineralogical, petrographic and lithological characters clearly indicate that the carbonate rocks represent an ancient analogue of the recent subtidal–supratidal environment near a platform margin (in Las Tienditas and Volcán). The stratigraphic analysis of the Puncoviscana Formation reflects the high frequency of alternations of shallowing and deepening facies successions formed on a continental borderland during the rifting stage of a passive margin development.

Evidence of the metamorphism and magmatism

The Tilcarian tecto-thermal event played a dominant role in the metamorphic evolution of the Puncoviscana folded belt. The metamorphism is present in the northern and eastern portion of the belt, where weakly metamorphosed sequences, not exceeding anchizone conditions (Rossi et al. 1992), are unconformably overlain by non-metamorphosed younger Paleozoic sediments. Metamorphism increases westwards and southwards and can reach greenschist and amphibolite grades and locally even granulite facies conditions. The climax of metamorphism may have occurred at the beginning of the Tilcarian orogeny, during which most of the plutonic rocks may have been generated. Many of them are considered to be dominantly and perhaps exclusively of crustal origin.

Pre-Tilcarian basic rocks

A major early phase of igneous activity occurs at various stratigraphic levels within the Puncoviscana Formation. The age of the widespread basic volcanic rocks is not known and in many cases the uncertain structural relationships between outcrops make it difficult to establish a precise lithostratigraphic scheme. Nevertheless, the compilation of selected geochemical data (Table 1) clearly shows that distinct groups can be identified within the spectrum of the Puncoviscana

Table 1 Representative analysis of major (weight percent) and trace elements (parts per million) of the volcanic rocks from the Puncoviscana Formation, Northwest Argentina

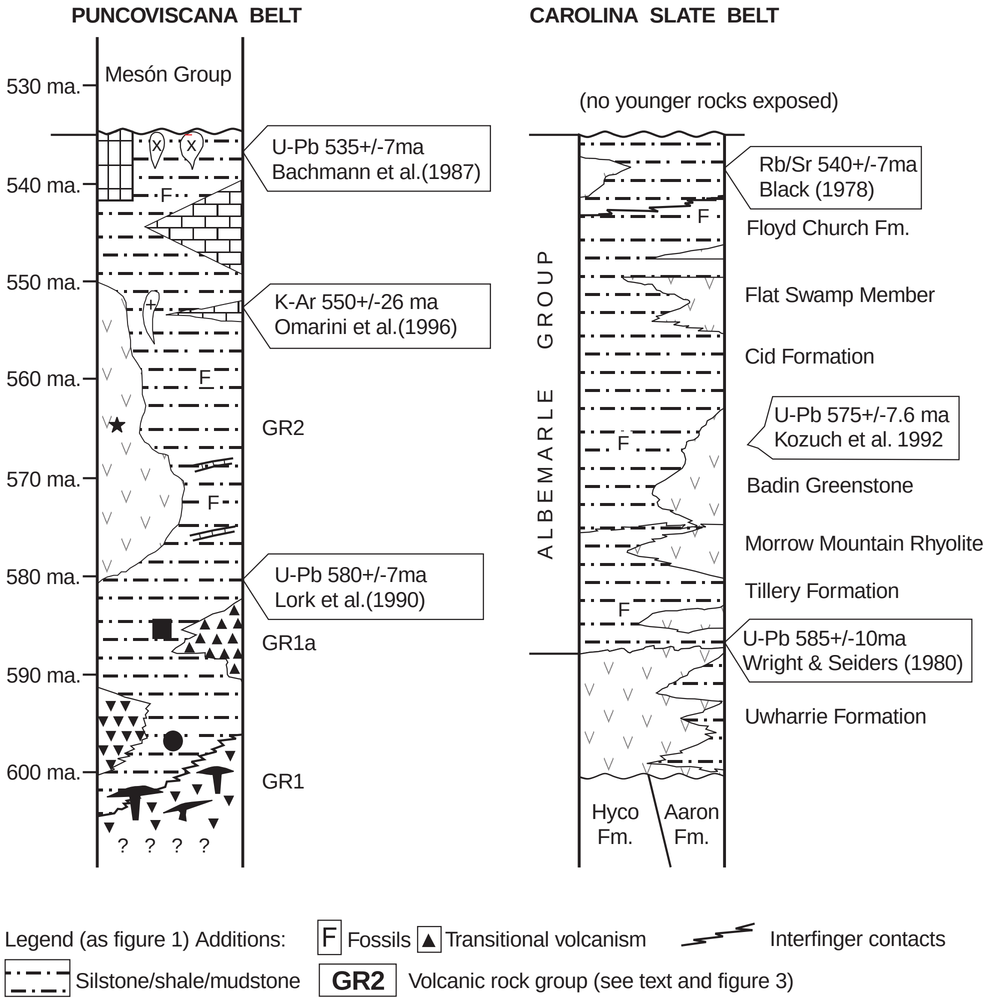
Sample	P-277	P-278	P-716	P-871	P-281	P-280	P-2	P-14	P-1	P-710	P-870
Si_2O	38.74	34.30	39.32	38.11	43.70	50.40	45.10	44.61	49.06	54.27	48.93
TiO_2	3.34	3.53	3.81	3.21	2.75	1.78	2.28	2.98	1.62	1.38	1.45
Al_2O_3	4.89	6.93	10.31	9.37	12.40	17.00	14.66	13.91	15.31	16.93	14.68
Fe_2O_3	12.82	13.60	15.86	15.03	12.40	8.45	10.84	12.29	11.82	10.45	14.22
MnO	0.17	0.23	0.23	0.30	0.17	0.15	0.17	0.27	0.15	0.10	0.11
MgO	25.86	12.00	13.14	15.83	8.77	2.94	11.69	11.08	7.16	5.42	6.01
CaO	11.15	15.50	7.09	10.70	8.46	6.39	7.67	8.04	3.77	3.68	5.99
Na_2O	0.11	0.71	1.60	0.90	3.31	4.73	1.69	2.18	4.55	3.40	3.05
K_2O	1.31	2.77	3.13	2.87	2.51	3.12	2.60	2.25	0.96	3.63	0.77
P_2O_5	1.64	1.84	1.09	0.89	1.00	0.53	0.26	0.30	0.25	0.40	0.35
LOI	–	7.55	4.42	2.79	2.55	3.30	3.00	2.02	5.23	3.34	5.23
Cr	812.00	345.00	381.00	493.00	396.00	323.00	813.00	158.00	268.00	422.00	390.00
Co	0.00	0.00	74.00	69.00	0.00	0.00	0.00	0.00	88.00	18.00	15.00
Ni	344.00	173.00	221.00	432.00	202.00	39.00	344.00	105.00	89.00	13.00	44.00
Sc	0.00	19.00	23.00	24.00	15.00	11.00	28.00	0.00	32.00	32.00	33.00
V	280.00	0.00	367.00	298.00	0.00	0.00	263.00	255.00	200.00	81.00	80.00
Zn	0.00	109.00	145.00	123.00	110.00	95.00	0.00	0.00	122.00	244.00	121.00
Rb	34.00	132.00	48.00	31.00	72.00	91.00	74.00	20.00	79.00	46.00	5.00
Ba	978.00	1260.00	1160.00	2960.00	1630.00	892.00	1758.00	340.00	726.00	854.00	269.00
Sr	1012.00	1640.00	714.00	902.00	1130.00	815.00	415.00	471.00	342.00	347.00	171.00
Ga	0.00	20.00	28.00	25.00	25.00	26.00	0.00	0.00	20.00	22.00	28.00
Ta	13.70	8.56	11.00	9.79	8.25	8.97	4.77	3.37	0.70	1.10	0.87
Nb	91.00	95.00	115.00	73.00	86.00	96.00	40.00	83.00	11.00	25.00	21.00
Zr	386.00	453.00	356.00	277.00	334.00	341.00	294.00	252.00	112.00	227.00	209.00
Y	36.00	47.00	30.00	24.00	28.00	26.00	18.00	18.00	29.00	44.00	35.00
Th	13.10	13.00	12.00	7.00	12.00	14.00	5.00	4.00	1.25	2.00	2.00
U	2.70	3.60	3.10	2.10	2.80	3.10	1.20	0.00	1.10	1.00	0.70
La	120.00	129.00	92.20	66.20	95.70	77.10	34.10	20.20	11.70	31.00	16.30
Ce	270.00	277.00	187.00	134.00	177.00	139.00	103.00	68.70	28.36	63.20	42.40
Nd	154.00	135.00	75.40	54.50	7 4.50	49.80	30.20	31.80	15.70	34.50	25.70
Sm	24.60	25.30	14.40	11.10	12.80	8.50	4.80	7.70	4.10	8.80	7.40
Eu	7.51	7.77	4.30	3.82	4.17	2.65	1.67	2.68	1.48	3.01	2.34
Gd	17.60	21.70	12.60	9.70	11.70	8.00	5.40	7.40	4.66	8.90	7.40
Dy	10.20	12.30	7.80	6.00	7.20	5.50	4.50	7.20	4.26	8.20	7.30
Er	3.20	4.30	3.10	2.30	2.70	2.50	2.30	2.90	2.39	4.80	3.70
Yb	1.80	2.60	7.50	1.60	1.80	2.00	1.80	2.00	1.90	4.80	3.30
Lu	0.24	0.13	0.29	0.21	0.05	0.07	0.24	0.30	0.32	0.77	0.44
Zr/Y	10.77	9.63	11.86	11.54	11.92	13.11	6.55	14.00	3.86	5.50	5.97
Zr/Nb	4.24	4.76	3.09	3.79	3.88	3.55	2.95	3.00	10.18	9.08	9.95
Th/Yb	7.27	5.00	7.50	1.45	6.60	7.00	2.77	2.00	0.52	0.41	0.60
Ta/Yb	7.61	3.29	6.87	2.03	4.58	4.13	2.65	1.68	0.36	0.22	0.26
Sm/Nd	0.15	0.18	0.19	0.20	0.17	0.17	15.00	0.24	0.26	0.25	0.26
Th/Y	0.36	0.27	0.40	0.29	0.42	1.80	0.27	0.22	0.03	0.04	0.05
Th/Nb	0.14	0.13	0.10	0.09	0.13	0.14	0.12	0.04	0.09	0.06	0.09
Nb/Y	2.52	2.02	3.83	3.04	3.07	3.69	2.22	4.61	0.37	0.56	0.60
Y/Nb	0.39	0.49	0.26	0.32	0.32	0.27	0.45	0.21	2.63	1.76	1.66
Ba/Nb	10.74	13.26	10.06	40.54	18.95	9.29	43.95	4.09	11.00	34.16	12.80
(La/Yb)n	44.71	33.30	38.66	9.25	35.66	25.85	12.70	6.77	4.13	8.83	8.61

basic volcanism as is illustrated on mantle-normalized diagrams (Fig. 3). With such data it is possible to evaluate changes in the magmatic evolution through time and the likely stratigraphic position of the volcanic units within the sedimentary sequences.

A tentative lithological column based on the geochemical characteristics of the magmatic products is shown in Fig. 2. In general, the volcanic succession can be divided into two geochemical groups according to the highly variable trace element abundance:

Group-1 facies are dominant in the lowest portion of the Puncoviscana Formation (Fig. 2) and consist of alkaline lavas, sills and dykes with oceanic-island to intraplate igneous affinities (Coira et al. 1990). The flows, sills and dykes range from alkaline olivine basalts and leucitites to rare alkaline lamproites which suggest lithospheric sources. The group is better identified by its K_2O/Na_2O ratio, greater than 3, and it is saturated to oversaturated in SiO_2. The leucitite-bearing rocks are commonly low in Al_2O_3, rich in K_2O and have a wide range of MgO contents from 12 to 25 wt.%, leading to high values of magnesium numbers [$Mg = 100\,Mg/(Mg + Fe_t)$] as high as 82. According to the classifications of Foley et al. (1987), these rocks can be considered as ultra-potassic. The trace element abundance is typical of primitive alkali basalts and leucitites from

Fig. 2 Comparative lithostratigraphy of the Puncoviscana belt (northwestern Argentina) and the Carolina Slate Belt (eastern North America). The dated sedimentary rocks are shown in relation to the trace fossils discussed



low-rate extensional continental zones, such as the East African rift (Table 1, P-277 and P-278). Figure 3 shows the incompatible trace element compositions on a chondrite-normalized diagram (Thompson et al. 1984). All these samples have higher contents of trace elements; however, profiles similar to those were observed in typical kimberlites. Their most striking geochemical feature are the high LILE and LREE enrichments with respect to HFSE and HREE. In detail, the spider diagrams are convex upwards with large relative depletion in K and Sr and peak at Tantalum rather than at Niobium. Ta, Nb and Ti abundance, for example, are of the order of magnitude similar to those of group-II kimberlites (Foley et al. 1987; Rock 1991).

The group-1 ultra-potassic rocks in general show high Zr/Y (~9.5–10.7) and low Zr/Nb (4.24–4.76) ratios, which is consistent with a pure mantle source (Seymour and Kumarapeli 1995). A similar inference can also be drawn from the systematic correlation between Th/Yb relative to Ta/Yb ratios. In Pearce element diagrams (Pearce 1982, 1983) the samples plot within the field of intraplate basalts derived from enriched mantle sources. By common consensus, such enrichments are characteristic for rocks derived from mantle plumes with OIB affinities (Stein and Hoffmann 1992; Weaver 1991; Fraser et al. 1985).

Within group 1 a subset of alkaline and sightly subalkaline basalts is identified by its generally lower trace element concentration (Table 1, P-280, P-281, P-716 and P-871). This series covers a much broader range of petrographic diversity with basanites, tephrites, alkaline olivine basalts (ankaramites) and trachyandesites.

SiO_2 contents range from 38.11 to 50.4 wt.% and are low in Al_2O_3 between 9.37 and 12.4 wt.%, except for the trachyandesites which commonly contain ~17 wt.%. Contents of total iron as Fe_2O_3 are high (>8.4 wt.%) and K_2O/Na_2O (>3 wt.%). The analyses also show high MgO and K_2O values. The lavas with high MgO have correspondingly high CaO and high $MgO/(MgO+Fe_t)$ values; Ni>300 ppm and Cr>350 ppm contents suggest that they may represent primary mantle-derived magmas.

The samples are all similar in their multi-element variation diagrams and REE patterns (Fig. 3), with an almost identical trace element abundance compared to a leucitite from Bufumbira (Thompson et al. 1984).

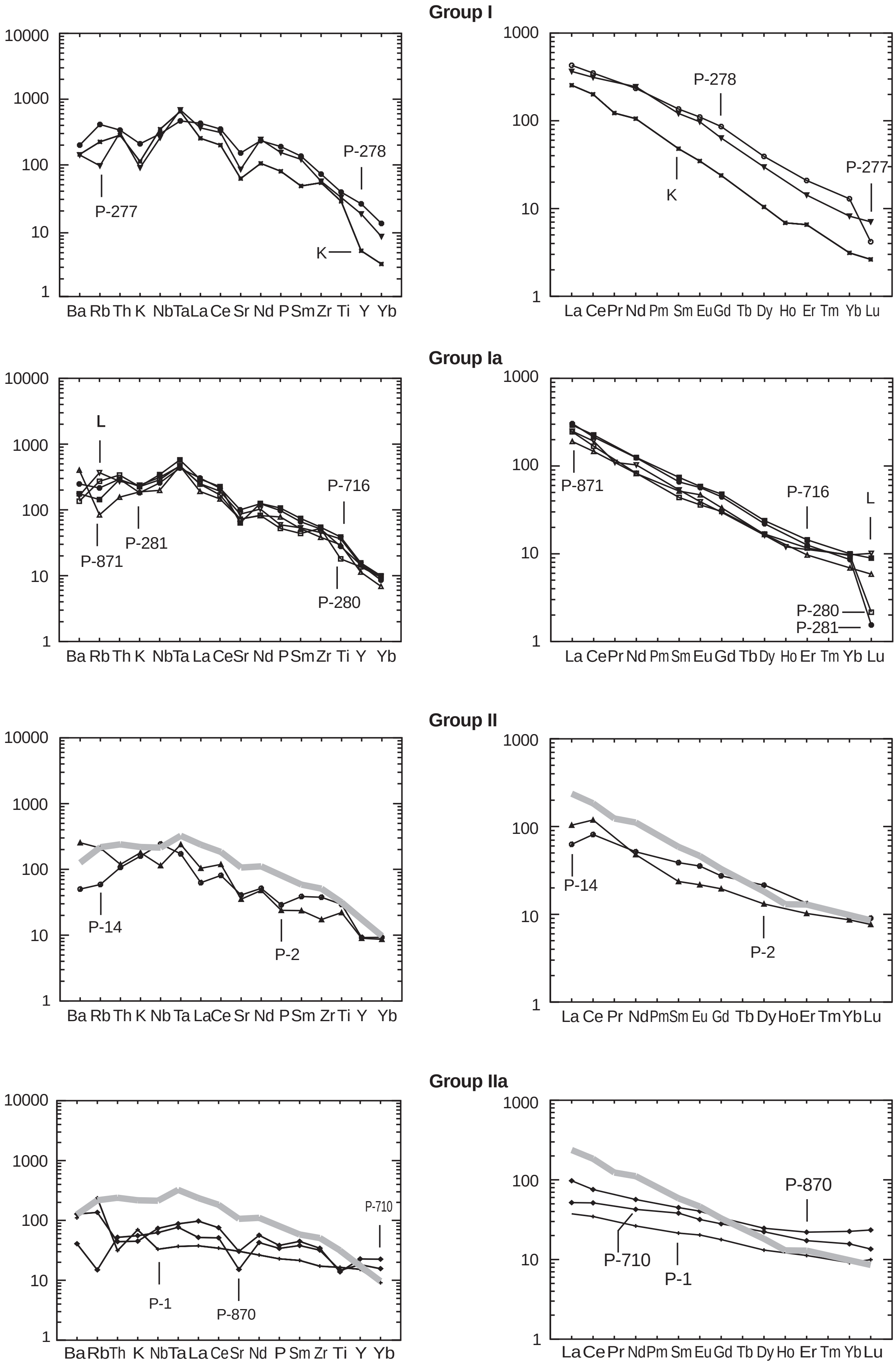

Group I
10000
1000
100
10
1
Ba Rb Th K Nb Ta La Ce Sr Nd P Sm Zr Ti Y Yb
P-277
P-278
K
1000
100
10
1
La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
P-278
K
P-277
Group Ia
L
P-871
P-281
P-716
P-280
P-871
P-716
L
P-280
P-281
Group II
P-14
P-2
P-14
P-2
Group IIa
P-710
P-1
P-870
P-870
P-710
P-1

Fig. 3 Representative normalized trace element and REE diagrams of volcanic rocks from Puncoviscana Formation. Normalization factors are from Thompson et al. (1984). *Shaded area* represents the range of the alkaline lavas from Cameroon line, continental sector. Also plotted for comparison are the kimberlite (*K*) from Lesotho and leucitite (*L*) from Bufunbira, both of the East African rift sector. Data source: rocks from Thompson et al. (1984) and Cameroon line from Fitton and Dunlop (1985)

Compared with the typical group-1 basic rocks (e.g. P-278), they have a more fractionated pattern for La, Ce, Nd, P, Sm, Zr and Y, with less-pronounced negative Sr troughs and similar Th, Nb and Ta contents.

The incompatible trace element concentrations and extreme LREE enrichment for the group-1 lavas are distinct from most island-arc lavas and related back-arc lavas. The geochemical characteristics mentioned previously are common in intraplate settings. They support the interpretation that all lavas have an asthenospheric (HIMU-OIB) source. This presupposition is consistent with the low incompatible trace element ratio such as Ba/Nb, Zr/Nb, Th/Nb and Th/Y (Table 1). In this context the remarkable geochemical similarity to the East African rift leucitites strongly suggests an identical genetic process.

Group-2 lavas range from typical alkaline basalts to transitional between alkaline and MORB-like basalts in character. The petrological and geochemical diversity and the voluminous nature of this volcanism suggest a contribution from two source component, coupled with the rift-drift transition stage. The alkaline are K/Ti-rich basalts with normative olivine compositions (Table 1, P-2 and P-14). They have low SiO_2 contents (~ 44 wt.%) and high TiO_2 (~ 2 wt.%) with a K_2O/Na_2O ratio slightly lower than 2. Total iron as Fe_2O_3 ranges from 10.8 to 12.3 wt.% with correspondingly high MgO and CaO contents. In contrast to island-arc and active continental margin basalts, the suite has higher Th/Yb and Ta/Yb ratios and plots in a similar position with the group-1 suite in discrimination diagrams (Pearce 1982, 1983), reflecting the influence of an enriched mantle source on their petrogenesis. However, in marked contrast to group-1 lavas, they show lower concentrations of incompatible trace elements and lower LREE/HREE ratios than those tholeiitic basalts that define the Cameroon line in its continental setting. The transitional lavas with tholeiitic affinity are high-Ti MORB-like basalts with range in SiO_2 between 48 and 54 wt.% (Fig. 4, P-1, P-710, P-870). They have quartz and hypersthene in their norms and display an Fe-enrichment trend on the AFM diagram. This series is similar in its major element composition to continental tholeiites, but differs from these in that the total abundance of incompatible elements, particularly of K_2O and P_2O_5, is low. The low abundance of Ti-group high-field-strength element (Nb, Ta, Zr, Y), and particularly the low Nb/Y (<0.6) and LREE/HREE ratios $(La/Yb)_n = 4.1–8.8$), are indicative of a transitional character to an incipient intra-arc rifting or primitive island arc just prior to the Tilcarian collisional event.

Tilcarian granitoids

The granitoids emplaced entirely in the Puncoviscana Formation display wide scatters of radiometric ages between 564 and 453 Ma. They commonly form a discontinuous and elongated (40-km-wide) plutonic belt with a NNE–SSW trend (see Fig. 11). Many plutons can be grouped on the basis of petrographic, chemical and isotopic features. The first-order subdivision of the granitoids is into two groups: the first type are the batholiths and stocks located in the northern portion of the belt including the Tastil, Fundiciones, Tipayoc and Cañani granites. Radiometric ages of these granites are sparse, but all data point to an emplacement within a short period of time. Most ages are into the 550- to 535-Ma interval. This is consistent with the stratigraphic relationships inferred from the unconformable superposition by lower Cambrian sediments (Meson Group).

The most widely exposed Tastil and Cañani batholiths consist of calc-alkaline biotite granites, hornblende granodiorites and tonalites that exhibit brittle to semi-brittle cataclastic fabric. Their textures vary from heterogranular, granoblastic to porphyritic, showing undulatory crystal extinction and poor subgrain development in quartz and feldspar. The most frequent association is plagioclase + alkali-feldspar + quartz + muscovite + biotite. Green hornblende is a dominant mineral facies in the Cañani granite. Accessory mineral phases are sthene, apatite, zircon and magnetite–ilmenite. Secondary minerals are muscovite, chlorite and calcite. The major and trace element abundance for Cañani and Tastil granites are homogeneous. Chemical analyses show variable SiO_2 (65–77%), low Al_2O_3 (11.4–15.5%) and low Na_2O contents relative to K_2O. In contrast, these granitoids have a high amount of ferromagnesian elements ($Fe_2O_3 + MgO + TiO_2$) ranging from 6.15 to 11.70%. Concentrations of CaO, Ni, Co, V, Rb, Sr and Y are highly variable, suggesting that considerable fractionation has taken place (Omarini et al. 1987a, b). Additional trace elements and isotopic determinations (Omarini et al. 1987b; Damm et al. 1991) have revealed that the Tastil granite contains a low Sr^{87}/Sr^{86} (0.7050) ratio and low O^{18} values, which range from $+9.8$ to $+12.4$. The Tastil granite has a U–Pb zircon age of 536 ± 7 Ma. Two ages of 519 and 534 ± 2 Ma (Bachmann et al. 1987) from Cañani granite suggest the same magmatic episode. Pluton contacts with the Puncoviscana Formation are sharp, and retrograded andalusite-bearing contact aureoles overprint the earliest tectonic fabrics of the host rock (Kilmurray et al. 1974). An early phase of intrusive activity is reflected by the emplacement of the Tipayoc granite (K/Ar age 550 ± 26 Ma; Omarini et al.

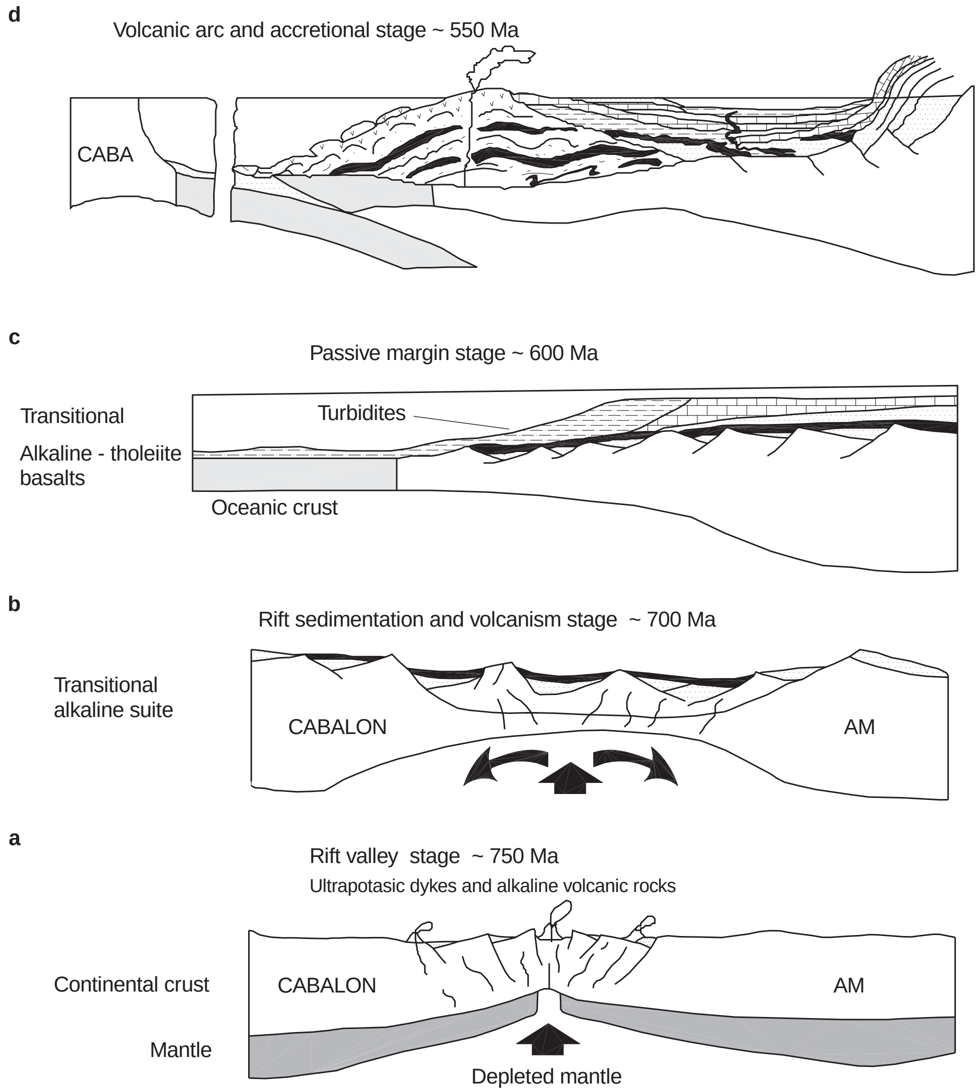


Fig. 4a–d Cross section shows the Gondwana continental margin evolution from late Precambrian to early Cambrian times. The geodynamical interpretation has been inferred from geological and geochemical data (see text for details)

1996). Its occurrence is observed in the areas of volcano-sedimentary syn-orogenic successions (i.e. central and western part of the Puncoviscana belt). Omarini et al. (1996) describe the stock as heterogeneous and dominantly composed of peraluminous leuco-granodiorite and minor quartzodiorite and trondhjemites dykes. The stock is foliated by shear fracture and mortar texture and exhibits a well-developed S–C fabric defined by mica folia alignments and blebs of variably recrystallized quartz-feldspar aggregates.

The second group of plutonic rocks is restricted along strike to the south of the Olacapato–El Toro fault system (see Fig. 11) and consists of volumetrically minor peraluminous two-mica granite, high-aluminium trondhjemites, aplites and pegmatites. Small stocks and complexes have been named Cachi Formation by Turner (1961). Ore prospects of rare earth mineral-bearing pegmatites in these stocks are abundant. The granitoid suite comprises approximately 14 separate stocks that are exposed over an area of 1640 km^2, running north–south over a distance of more than 150 km near the western edge of the belt. Galliski (1983), Galliski et al. (1990) and Schön and Miller (1990) describe the granites as heterogeneous and dominantly composed of oligoclase, quartz, perthitic alkali feldspar and Al-rich minerals such as muscovite, cordierite and sillimanite. Epidote and sphene are always found in close association with biotite. They are frequently deformed and foliated showing a good S–C fabric defined by mica-plate alignments and folia or blebs of variably recrystallized quartz-feldspar aggregates. These rocks have a small range in silica contents (69–74%) and are distinctly peraluminous with a high Al/(Na+K+Ca) ratio at similar SiO_2 abundances, compared with the trondhjemites of the Tipayoc stock. The rocks are also poor in ferromagnesian elements ($Fe_2O_3+MgO+TiO_2 \leq 5$) and rich in Na_2O relative to K_2O and CaO. All granitoids give high fractionated REE with LREE-enriched and accentuated concavity of the HREE patterns (Galliski and Miller 1989). Radiometric ages of the granites scatter considerably, but all dates point to an emplacement between 563 and 453 Ma. This is clear evidence that the southern part of the belt was affected by at least two major episodes of magmatism. The first episode was in the Late Proterozoic and the second in the Ordovician. Some significant conclusions about these granites can now be drawn. There is general agreement that the suite might be correlated with different sources (Toselli 1992). The Eocambrian granites with minor trondhjemites are thought to derive from a primitive and aborted magmatic arc before the Cuyania–Arequipa–Belen–Antofalla collision (CABA terrane, after Omarini y Sureda 1994). The Ordovician granites may be crust-derived granitoids forming large belts restricted to the western margin of the Pampean range, and have been termed epidote-bearing granitoid suite by Saavedra et al. (1987).

A petrogenetic model for the tectonic setting of the Puncoviscana belt

The conclusion reached from the foregoing geochemical analysis indicates two distinct sources in the generation of the mafic magmatism in the Puncoviscana Formation. One source, highly alkalic in nature (group 1 and 1a suite; Fig. 3), was characterized by an extremely incompatible element enrichment relative to N-MORB and may be related to a mantle plume source. The other source (groups 2 and 2a suite; Fig. 3) shows transitional characteristics from alkaline OIB to MORB sources, probably accomplished with the addition of subduction components. If the participation of the previously mentioned sources in the petrogenesis of the basic rocks is accepted, the magmatism in this region may be the result of a particular tectonic environment. It is thus suggested that the studied part of Puncoviscana belt and adjacent parts of the Pampean craton show a set of magmatic signatures reflecting the evolution of the rift and rift-drift transition stage during the breakup of the Rodinia supercontinent. The possible geodynamical scenario could have developed in different steps as shown in Fig. 4. A first stage ($\sim$750–650 Ma; Fig. 4a) involves crustal attenuation over a rising mantle plume. Group-1 lavas were emplaced synchronously with the onset of rifting and sill intrusions. Dyke injections and lava flows were restricted entirely to shallow-water clastic sediments.

To generate the limited geochemical spectrum of group 1, a very low degree of partial melting by mantle-plume-derived material is required. The low Zr/Nb and Y/Nb ratio supports this assumption and, due to an effect of element partitioning in low-degree source melting, the high MREE/HREE ratio is indicative of residual garnet in the source (Edwards et al. 1994). Assuming that this is the case, the degree of partial melting of the pre/syn-extensional ultra-potassic rocks in the Puncoviscana Formation can be produced by approximately 1–5% partial melting of the fertile garnet lherzolite according to the batch-melting model proposed by Bradshow et al. (1993). In subsequent steps (700–600 Ma; Fig. 4b–c), lateral spreading increased subsidence and the basin became filled by pronounced lithological variations mostly of turbiditic character. In this step, the ascending mantle plume head intersected the base of the lithosphere and initiated the partial melting (mixing OIB in character) as commonly happens in intraplate volcanism. The mixing model is consistent with the transitional geochemical spectrum found between the group-1 and group-2 lavas. Generation of principally tholeiites with normative quartz and minor transitional alkaline basalts reflects the magmatic evolution and a more advanced stage in the rifting process. It is believed that a true oceanic crust may have developed at this stage (Fig. 4c). The time related to the change in the composition of the lavas also explains the generally depleted nature of their trace element patterns. The overall geochemical affinities of the group-2 basalts (P2–P14) to continental trap basalt support a model in which the magma source is garnet free and probably spinel rich. Such spinel-bearing mantle source requires melt generation at depths of $<$80 km (Bradshow et al. 1993). Similar results have been observed in other extensional provinces, such as Deccan, Arabian-Nubian shield, and Basin and Range (Stein and Hofmann 1992; Withe and McKenzie 1989).

In contrast, the samples P870, P710 and P1 have comparatively smooth, normalized patterns of trace elements and higher Sm/Nd ratios (0.25–0.28) similar to transitional OIB- to MORB-type basalts. In particular, the sample P1 displays the lowest Nb and Ta contents at similar Th concentrations, which may be connected to a magma-bearing incipient subduction. The lack of a strong subduction signature is consistent with the idea that the partial melting process was not sufficiently hydrous to produce a marked depletion of the Nb and Ta (Pe-Piper and Piper 1989). A similar conclusion can be drawn from titanium. The high Ti contents in the lavas could be due to oxygen pressure in the derivative magma low enough to permit an extensive Ti-magnetite fractionation (Edwards et al. 1994).

In summary, these lavas, identified by high Ti-tholeiites, represent the latest intense volcanic episode in the development of the Puncoviscana Formation (580–550 Ma) associated with volcaniclastic sediments and carbonate platforms (Fig. 4d). The geochemical and geological considerations very strongly support the evidence of the CABA terrane collision with the western margin of proto-Gondwana during the Late Precambrian–Early Cambrian time.

The residual gravity field in the proto-Gondwana terranes

The segment of the Central Andes between 20°S to 28°S shows an anomalous gravity field which consists of numerous local and regional components and fits in the morphostructural units in most cases (see Fig. 5a; Götze et al. 1994, 1996; Götze and Kirchner 1997).

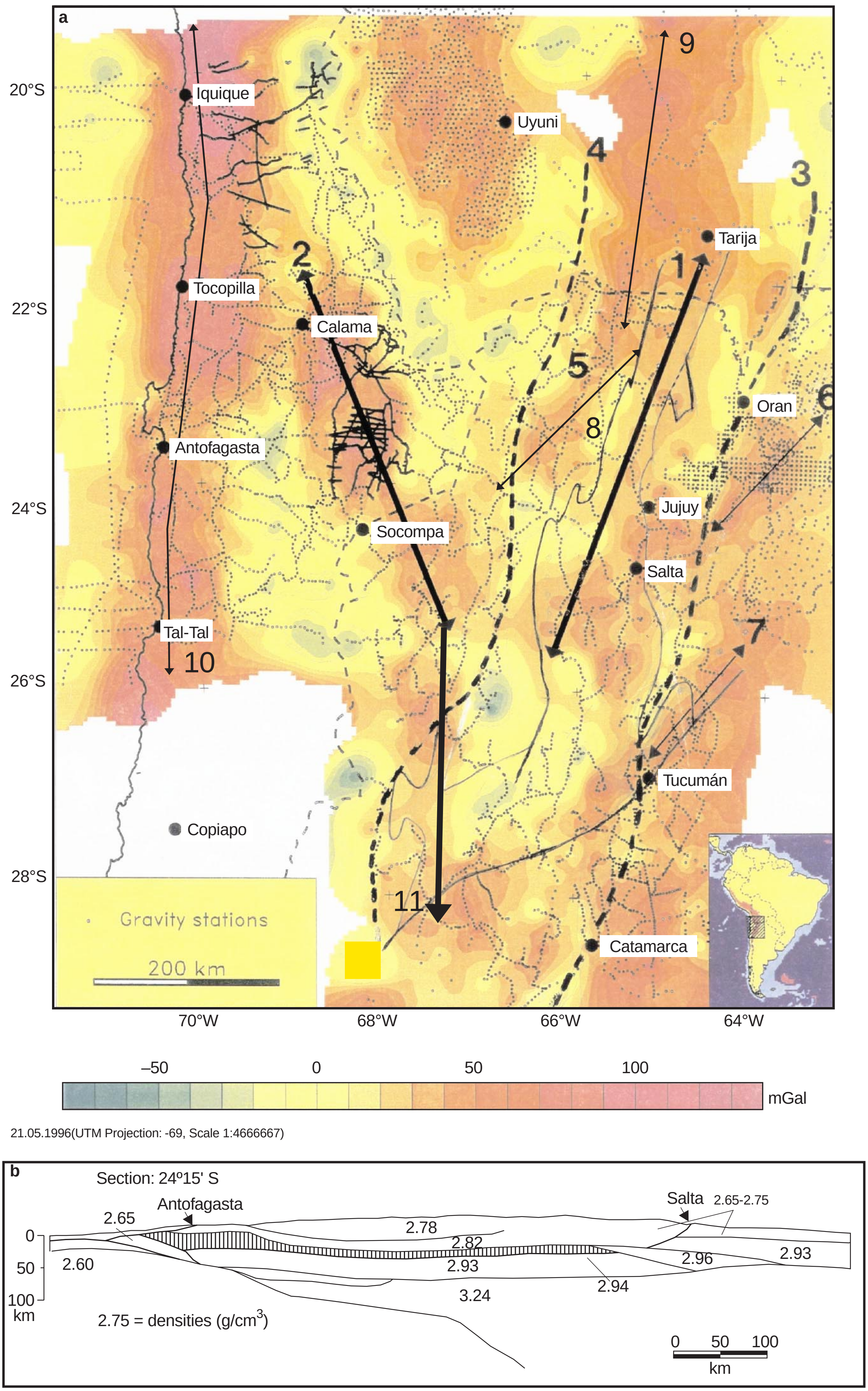

a
20°S
22°S
24°S
26°S
28°S
70°W
68°W
66°W
64°W
Iquique
Tocopilla
Calama
Antofagasta
Socompa
Tal-Tal
Copiapo
Uyuni
Tarija
Oran
Jujuy
Salta
Tucumán
Catamarca
1
2
3
4
5
6
7
8
9
10
11
Gravity stations
200 km
–50
0
50
100
mGal
21.05.1996(UTM Projection: -69, Scale 1:4666667)
b
Section: 24º15' S
Antofagasta
Salta
2.65
2.65-2.75
2.78
2.82
2.93
2.60
2.96
2.93
2.94
3.24
0
50
100
km
2.75 = densities (g/cm3)
0 50 100
km

Fig. 5 a Central Andes residual gravity map. The *thick dashed lines* indicate the inferred Puncoviscana belt boundaries with the pre-Tilcarian (*3*) and Tilcarian (*4*) sutures. The *thick solid lines* indicate the trend of the residual gravity anomaly in coincidence with magmatic arcs. *1* Late Precambrian–early Cambrian; *2* Late Ordovician; *10* Middle Jurassic. The *thin lines* (*6–9*) indicate the trend of Jurassic–Cretaceous crustal gravity anomalies along rifted areas (*5*). Shallow high positive gravity anomaly of >30 mGa (see text for details). *11* Aconquija lineament. **b** Interpreted density model, at approximately 24° 15' S, of the uppermost mantle and the crust from Pacific Ocean to Chaco Plains. The high-density block beneath Salta was introduced by gravity modeling. *Vertically lined areas* are a low-velocity zone

Three distinct anomalous domains have been outlined:

1. A prominent continuous positive north–south anomaly is located along the Chile margin (10 in Fig. 5a) parallel or astride to the axis of the exposed portions of the Coastal Cordillera belt (Jurassic to Lower Cretaceous).
2. A broad regional gravity high with NW–SE trend extends from the northern Domeyko Cordillera to the Fiambala ranges (2 in Fig. 5a). These extremely high gravity values can reflect the signature of a Precambrian–Early Paleozoic basement beneath the Western Cordillera (e.g. Götze et al. 1988; Götze and Kirchner 1997).
3. Another NNE–SSW gravity anomaly is located eastward to the present magmatic arc and covers the entire Eastern Cordillera belt (1 in Fig. 5a). The western border (4 in Fig. 5a) extends beneath the Puna plateau and is well correlated with the boundary between Puna and the eastern Puna mylonite zone. The eastern border (3 in Fig. 5a) is interpreted by Götze et al. (1994) as a transition zone between different crust types represented by the Eastern Cordillera and the Subandean foreland. This distinctive signature probably marks the west-dipping suture zone between the Brazilian craton and the Puncoviscana belt.

A previous gravity interpretation (Strunk 1990; Omarini and Götze 1991) postulated the presence of dense bodies with a calculated rock density of 2960 kg/m^3 below the Eastern Cordillera (6–8 km up to 24 km; Fig. 5b).

In the northwestern portion of the inferred Puncoviscana belt boundaries (5 in Fig 5a) there is a relatively shallow highly positive anomaly of more than 30×10^{-5} m/s^2. Gravity modelling (Gangui and Götze 1996) shows the presence of high density bodies with a calculated density of 2950 kg/m^3 and thicknesses of about 8 km in the basement below a sedimentary and volcanoclastic Ordovician cover. As reported by Gangui and Götze (1996) this gravity anomaly can be explained by assuming a continent–continent accretion of a Late Ordovician magmatic arc (PM vs CABA; PM is Precordillera-Mejillonia terrane, modified from Omarini y Sureda 1994). It is believed that the existence of similar gravity anomaly pattern in an adjacent Precambrian–Lower Cambrian terrane strongly suggests that the positive gravity is caused by older structures, which had been overprinted by the Cretaceous rift orogenesis. The presence of a decollement level in the upper crust, clearly seen also in reflection seismic data (Gangui and Götze 1996), appears to be an attractive explanation since it allows for large-scale sub-horizontal displacements of the middle crust towards the east. Thus, the pronounced gravity bodies (massive granulites, e.g. xenoliths) within Cordillera Oriental of Salta and Jujuy may be ascribed to the mechanical processes involved in the consolidation of the Puncoviscana belt during the CABA/Pampia-Amazonian collision in the Late Proterozoic. In this context some important conclusions are established:

1. The regional geology and gravity signature is dominated by a linear NNE–SSW trend of granites and volcanic rocks related to the accretion of a linear volcanic belt and terrane. Their juxtaposition with Palaeoproterozoic cores indicates substantial crustal mobility; thus, the sheared western zones of the Puncoviscana belt is considered as expressive of the Tilcarian suture (4 in Fig. 5a and 1 in Fig. 11).
2. In the major Puncoviscana belt (area between 3 and 4 in Fig. 5a) there are many individual crustal blocks the boundaries of which coincide with gradients between major elongated, subparallel, positive and negative anomalies. Studies have shown that the gravity highs from different blocks have the same feature. This is not what would be expected if the Puncoviscana belt comprised numerous accreted terranes with separate histories, as suggested by Mon and Hongn (1996). This can be better explained by structures being formed while younger crust was thrusted against older lithosphere (9 in Fig. 11). The consequent pre-Tilcarian suture shows a negative gravity pattern (3 in Fig. 5a).
3. Outside of the Puncoviscana belt, another anomalous gravity trend coinciding with the Western Cordillera magmatic arc (Omarini and Sureda 1994; axis 2 in Fig. 5a) is evidence for relicts of Late Ordovician structures from magmatic Ocloyic episodes of the Famatinean belt (7 in Fig. 11).
4. In the pre-Andean rift of the northwestern Argentina (Jurassic–Cretaceous boundary), the intrusion and extrusion of igneous bodies from ultra-potassic to calc-alkaline differentiation trend shows small and widespread outcrops. Isolated complex batholiths (Tusaquillas) approach in size several stocks of granites (Abra Laite, Aguilar, Rangel, Hornillos). Red beds with intercalated alkaline basalts, basanites, carbonatites and tephrite dykes of the Salta Group are related to the southern branch of the Ayopaya rift system (9 in Fig. 5a; Sureda et al. 1989). Since the Tres Cruces rifted triple point, the Salinas Grandes branch is coincident with NE–SW highly positive anomalies (8 in Fig. 5a). The Michicola and Aconquija lineaments have similar trend. The very

high gravity anomalies are in these narrow NE–SW structures within the basement (6–8 in Fig. 5a). Later at the Araucarian phase, the xenolith evidence (Lucassen et al. 1998) supports the great amount of basic rocks that has been generated in dense granulite layers within the lower/middle crust. The gravity trends, linked to the remobilized crust, can be traced over long distances, and their well-defined pattern does not correlate with the gravity signature of adjacent areas. Here it seems reasonable to think that the gravimetric signature of the pre-Mesozoic basement was modified by reworking during the Jurassic-Cretaceous crustal extension. This pattern would have also been overprinted to the rock-density signature of the Puncoviscana belt.

5. During the Andean cycle (post-Inca phase from Middle Eocene), major overplating events played an important role in the formation and evolution of the lower crust. It is clear that the present Andean magmatic arc over the high Cordillera has a negative gravity pattern. Apparently, on the east slope, the crust in the foreland is not entirely uniform. However, the definite positive gravity anomalies are strong on the actual Pacific Chilean coast and have a north–south trend. A previous interpretation of these anomalies has been given by Götze et al. (1988) to the La Negra Middle Jurassic magmatic arc (axis 10 in Fig. 5a).

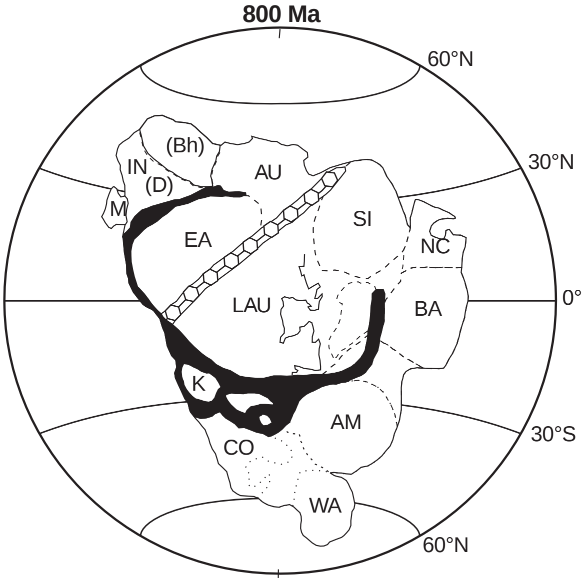


Fig. 6 The Rodinia supercontinent as assembled at ca. 800 Ma Laurentia-Baltica and Laurentia-East Gondwana (SWEAT) reconstructions follow the interpretation by Torsvik et al. (1986). North China is positioned according to Unrug (1996). Kalahari, Congo, West Africa and Amazonia fits modified from Moores (1991). *Black symbols* show the Grenvillian mobile belt distribution (900–800 Ma), *hexagonal symbols show* the Proto-Pacific rift margin (750–725 Ma; Powell et al. 1993; Dalziel et al. 1994). *IN* India; *M* Madagascar; *Bh* Budelkhand; *AU* Australia; *EA* East Antarctica; *Si* Siberia; *NC* North Carolina; *BA* Baltica; *LAU* Laurentia; *AM* Amazonia; *WA* West Africa; *CO* Congo; *K* Kalahari

Puncoviscana belt evolution: from Rodinia breakup to the Gondwana configuration

According to petrogenetic models and geological and geophysical observations, the evolution of the Puncoviscana belt was probably related to an extensional tectonic regime which changed into a well-developed active (i.e. compressional) plate margin (Fig. 4d). This interpretation provides a new perspective on the hypothetical Late Precambrian supercontinent (Rodinia or Pangea II) and contains the suggestion that between 750 and 650 Ma (minimum) proto-Gondwana separated from the North American (Laurentia) continent.

The Late Precambrian reconstruction (Fig. 6) was originally proposed on the basis of palaeomagnetic data (McWillians 1981; Piper 1982; Van der Voo 1988; D'Agrella-Filho et al. 1998) and of an extensive "Grenvillian orogenic belt" (1.3–0.9 Ga; Moore 1991; Dalziel 1991), which presently forms isolated blocks on different continents. Another convincing correlation has been suggested on the basis of palaeontological and stratigraphic affinities between the Precordillera terrane and the Appalachian Ouachita orogen (Astini et al. 1995, 1996; Benedetto 1993). Dalla Salda et al. (1992) have suggested an Ordovician collision between Laurentia and proto-Gondwana (470–460 Ma) to explain the Famatinian orogenic belt. In this context, the "Occidentalia terrane" has been reinterpreted as the whole Laurentia continent colliding with proto-Gondwana by the end of the Ordovician. However, this continent–continent collision hypothesis does not explain the pre-Ordovician compressional history of the proto-Gondwana margin – particularly the early Cambrian Tilcarian orogeny – preserved in the Puncoviscana Formation.

It is clear that these unsolved problems are linked with a major question concerning the palaeoposition of Laurentia vs Pampia-Amazonia. In an attempt to explain the Puncoviscana belt evolution, we propose an evolutionary model that starts with a continental Rodinia breakup (see Figs. 7 and 10: Cabalon nuclei) and the formation of several micro-plate interactions during symmetrical drift at the Laurentian and Pampia-Amazonian borders. The accretion of Cabalon terrane comprises a very long Early Phanerozoic history. There is a clear diachronism in the complex suturing between different accreted terranes (mainly CABA, Precordillera-Mejillonia and Chilenia) and their relation to the eastward subduction of slabs along the active continental margins of South America.

The global reconstruction emerges from palaeontological (trace fossil), sedimentary and the magmatic affinities between the Puncoviscana belt (proto-Gondwana) and the Carolina slate belt (Laurentia).

The Carolina slate belt runs northeast–southwest for 600 km from Virginia to Georgia and forms part of the

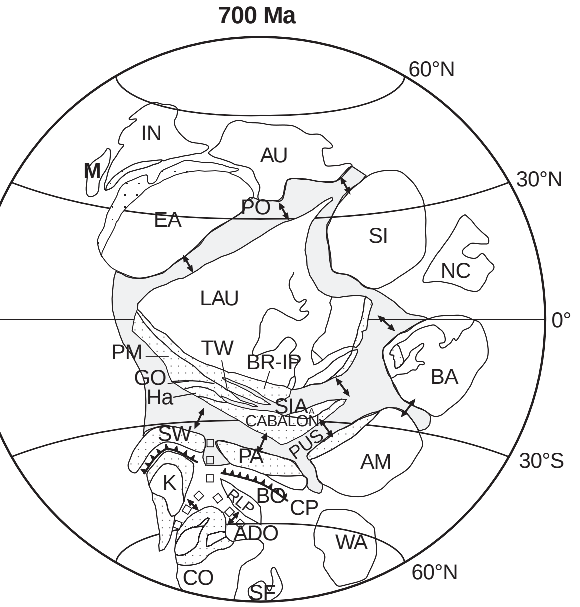


Fig. 7 Early Neoproterozoic reconstruction (ca. 700 Ma) shows the initial stage of the break-up of the Rodinia and Puncoviscana-type basin distribution (*grey area*). Abbreviations as in Fig. 6. *BR-IP* Eastern Blue Ridge-Inner Piedmont; *CABALON* for details see Fig. 10; *SIA* South Iapetus Ocean; *PO* Proto-Pacific Ocean; *PUS* Puncoviscana Sea; *PA* Pampia; *RLP* Rio de la Plata; *SF* Sao Francisco; *ADO* Adamastor Ocean; *BO* Brasilides Ocean; *SW* hypothetical Somuncura-Deseado-Malvinas-Wedell terrane; *Ha* Hatteras terrane; *GO* Goochland terrane; *PM* Precordillera-Mejillonia terrane; *TW* Tawson block; *CP* Córdoba-Paraguay magmatic arc. *Stippled areas* dismembered Grenvillian orogen

super terrane that extends the full length of the Appalachian orogen from Alabama to Newfoundland (Williams and Hatcher 1982, 1983; Hatcher 1989). This belt consists of pelites and greywackes with subordinate conglomerates and quartz arenites. It also includes bimodal volcanic rocks that interfinger with laminated mudstone and sandstone (in the Albemarle Group; Milton 1984; Secor et al. 1989), similar to marine turbidites of the Puncoviscana Formation (see Omarini and Baldis 1984; Jêzek 1990). The isotopic ages range from late Precambrian to Cambrian (Goldsmith and Secor 1993; Kozuch et al. 1992). These ages are also supported by body and trace fossils present principally in the Floyd Church Formation (*Pteridinium:* Gibson et al. 1984; *Oldhamia simplex, Vendospica graptoliforme:* Seilacher and Pflüger 1992), which have been correlated with worldwide Ediacara biota of Vendian times (Gibson et al. 1984). Other traces that appear to be restricted to Vendian strata, such as *Harlaniella podolica Sokolov,* have also been recorded in the Chapel Island Formation in Newfoundland (Bengtson and Fletcher 1983; Crimes and Anderson 1985).

The trace fossils of the Puncoviscana belt are particularly known through Aceñolaza (1978), Aceñolaza and Durand (1986) and Durand (1994), who recorded 23 ichnogenera including: *Gordia, Helminthopsis, Planolites, Tasmanadia, Oldhamia, Didymaulichus, Dimorphichnus, Diplichnites, Neonereites, Phycodes, Scolicia, Protichnites, Protovirgularia, Torrowangea, Sekwia, Beltanelloides* and*Paliella*. A similar ichnofaunistic association has also been recorded from Tucavaca belt of the eastern Bolivian and the Paraguay–Araguaia belts (O'Connor and Welde 1986).

New studies revealed that the Puncoviscana trace fossils reflect a deep-sea environment and are Cambrian in age, but not younger than *Lower* Cambrian, because the overlaying shallow marine sandstones of the Meson Group contain the Atdabanian trace fossil *Syringomorpha nilssoni.* Nevertheless, we can observe the expansion of the Cambrian Agronomic Revolution (Seilacher and Pflüger 1994) into the deep sea, because an *Oldhamia* community related to matgrounds is replaced by a richer and more bioturbational trace fossil assemblage in higher parts. By that we regard it more appropriate to assume a maximum age of 545 Ma for the Precambrian–Cambrian boundary in South America, which is in accordance with the new Geological Phanerozoic time scale of Gradstein and Ogg (1996).

The foregoing data show that similar benthic communities occur in similar environments at similar times, and thus that benthic assemblages can be used to correlate different terranes. The ichnofauna evidence therefore leads us to believe that Laurentia and the proto-Gondwana continent were a conjugate rift pair in the supercontinent Rodinia during the late Precambrian as shown in Fig. 7.

The fragmentation of Rodinia, dated 750–725 Ma (Powell et al. 1994; Hoffman 1991), produced at least two ocean basins and involved three large-scale extensional rift zones from which the Pan African–Brasilian orogens were born (SIAR, PUR and NbR; see Fig. 10). The rifting of Laurentia from West Rodinia produced the proto-Pacific ocean (Torsvik et al. 1996). Intracontinental rupture at this time is also indicated by the formation of the Brasilian ocean and the Nosib rift, which predate the Otavi drift-passive margin formed at 750–600 Ma (Unrug 1996; Prave 1996, and references therein). The Adamastor ocean is the consequence of a more accentuated drifting between Congo and Río de la Plata cratons; however, a difference of opinion persists over its closure. Recent reviews (Unrug 1996; Prave 1996) support a tectonic model in which the Congo and Río de la Plata cratons collide ($\sim$600 Ma) prior to Kalahari–Congo collision ($\sim$550 Ma).

The rift-system between the Laurentia and Amazonia–Pampia shields is also geologically feasible according to the current evidence of rift-related magmatism in both continental margins. The ultrapotassic dykes and alkaline volcanic rocks within the Puncoviscana belt are clear evidence of mantle plume activity. The presence of Late Precambrian rocks of continental rift trend in the Avalon composite terrane (see Dallmeyer 1989; Keppie 1989; Murphy et al. 1990) is believed to be the result of similar mantle plume activity. The Tibbit Hill Formation in Newfoundland shows a range of volcanic rocks with alkaline and tholeiitic affinities indicating a rapid phase of rifting. This volcanic event was recorded 35 Ma after the emplacement of the Grenville Dyke Swarm in the Sutton Mountains (Kumarapeli 1993; Seymour and Kumarapeli 1995). This implies that the separation could have begun at 750–700 Ma (Krogh et al. 1983) and involved an asymmetrical rift propagation from north to south along the Laurentia and Amazonia–Pampia connection. Such arguments imply a diachronous evolution of the Iapetus ocean and the Puncoviscana sea. We think the opening of the Puncoviscana basin was prior to the initiation of the Iapetus ocean, at least in the southern portion of the eastern Laurentia margin. In this segment the rift-to-drift transition probably was completed during Vendian time (600–580 Ma), which suggests a complete breakup of a large crustal fragment between the two Archean nuclei. The primitive continental shield in the core of Rodinia is named herein Cabalon (see Figs. 7, 10). This proposed hypothetical continent is interpreted as a "missing superterrane" which disintegrated into a lot of slivers. This supports a symmetrical and equivalent geodynamical evolution between the Laurentia and Amazonia–Pampia margins from late Precambrian to Paleozoic times (Fig. 10).

Another aspect of the Cabalon breakup leads to an interesting prediction about the subsequent evolution of the Iapetus ocean. During Vendian times the redistribution of fragmented Rodinia was characterized by an exceptionally high plate velocity up to 20 cm/year (Torsvik et al. 1996). This situation may have been accompanied by a metastable Cabalon plate and the rapid latitudinal drift of minor terranes. In this tectonic scenario the fragmentation of the Cabalon superterrane provides a coherent solution to the geological history of eastern Laurentia and proto-Gondwana margins.

A summary for the disintegration of this lost continent is given in Figs. 7, 8 and 10 according to the tectonic synthesis for the southern Appalachian orogen proposed by Muller and Chapin (1984), Horton et al. (1989) and Condie (1990). This sector has traditionally been interpreted as a succession of compressional events in Paleozoic times from an accretional terrane system. Prior to this, Late Proterozoic to Early Paleozoic sedimentary and volcanic rocks indicate that they were formed in a rifted environment close to the Iapetus ocean opening. The sedimentary record of the passive margin in the Blue Ridge and the Valley and Ridge provinces can be grouped into two sequences (Wehr and Glover 1985): (a) older pre-Catoctin sequences (Late Proterozoic) identified by immature clastic and volcanic rocks which include the Granfather, Ashe, Mount Roger, Mechun, Swift and Fouquier formations; (b) a younger post-Catoctin suite (Late Proterozoic–Early Paleozoic) dominated by clastic sedimentary rocks including Catoctin and Alligator formations as well as the Evington and Chilhowe groups.

During latest Precambrian–Early Cambrian times

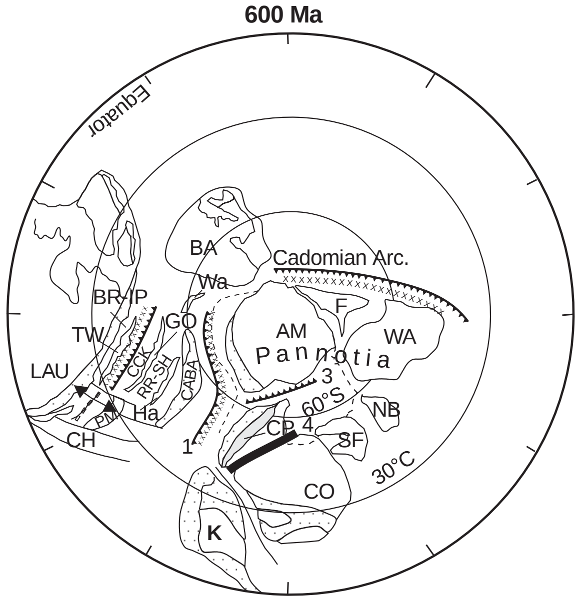


Fig. 8 Late Vendian (ca. 600 Ma) palaeogeographic reconstruction. Northern South America (*AM*) positions modified from Torsvik et al. (1996); Baltica based on McKerrow et al. (1992); West Africa and Nigeria-Borborena (*NB*) as in Unrug (1996); Laurentia as in Torsvik et al. (1996); Congo and Kalahari craton positions based on data suggesting that the Damara orogen was intracratonic and the Rio de la Plata-Congo collided prior to the collision of the Kalahari vs Congo (see Prave 1996). F Florida Block; CH Chilenia terrane; RR-SH Roanoke Rapids and Spring Hope belt; CCK Charlotte-Carolina-Kioke belt. Wa West Avalonia; CABA Cuyania-Antofalla-Belen-Arequipa terrane; *1* Puncoviscana-Tucavaca magmatic arc; *3* Paraguay-Araguay magmatic arc

there was a fundamental change in plate motion. The ending of the Blue Ridge separation was due to the convergence of the Towson block, integrated by the Baltimore gneiss and Glenarm Supergroup, which are considered as a displaced terrane rifted from Laurentia (Thomas 1977; Muller and Chapin 1984). The terrane convergence and the metamorphic lithofacies profiles suggest that subduction was predominantly cratonward-directed beneath the Laurentian shield (see Fig. 10).

Stratigraphic, petrological and geochronological data indicate that successive magmatic arcs with associated volcano-sedimentary sequences and neighbouring by oldest terranes with Grenville ages were formed between 600 and 450 Ma. The Carolina terrane (Secor et al. 1989) comprises the volcano-sedimentary sequences traditionally assigned to the Carolina Slate Belt including the Charlotte, Belair, Kiokee as well as part of the King Mountain belt. Figure 2 summarizes the stratigraphy of the Albemarle area with ages ranging from 586 ± 10 Ma (U–Pb zircon; Wright and Seiders 1980) to 540 ± 7 Ma (Rb–Sr whole rock; Black 1978).

The evolution and relation of Late Proterozoic and Cambrian rocks of the Carolina terrane has led to a divergence of opinions (Dennis and Shervais 1991;

Roger 1982; Milton and Reinhardt 1980). However, stratigraphic and petrological data indicate that their formations were probably deposited in a back-arc setting and have an arc volcanogenic provenance. The Belair belt and part of the Kiokee belt have been interpreted as a volcanic arc (Maher et al. 1981). This implies an evolution along a subduction zone probably connected to the convergence of the Goochland terrane. Rocks of similar affinity have been identified in several areas along the eastern board of the Goochland and Carolina terranes. The Roanoke Rapids terrane has transitional characteristics between marginal marine-shelf deposits and volcanogenic sequences (Horton and Stoddard 1986). The rocks associated with the Spring Hope terrane are representative of a volcanic arc (Boltin and Stoddard 1987) and presumably result from subduction by the convergence of the Hatteras terrane against the Roanoke Rapids–Spring Hope belt during the Acadian orogeny (see Figs. 8–10; Horton et al. 1989).

During the postulated Cabalon fragmentation a remnant block named CABA collided at 530–520 Ma with the western margin of the ephemeral Early Paleozoic Pannotia supercontinent (Figs. 8–10). The CABA terrane (including the Cuyania, Antofalla, Belen and Arequipa blocks) is defined in this paper as a very large composite terrane with a Grenville-age basement. As a consequence, the early proto-oceanic rift between Laurentia and Amazonia was aborted and an active island-arc-type margin was formed along the central western Pannotia border. The model shows the timing and stratigraphic setting for this volcanism (1 in Fig. 8), with the ensuing amalgamation of CABA against Pannotia, which must have occurred rapidly. This configuration is consistent with the concept that the terminal collision was coeval with the Tilcarian orogeny at 530–520 Ma, as has been suggested by Omarini and Sureda (1993).

The alternative of an Ocloyic continent–continent collision between Laurentia and Proto-Gondwana across the Appalachian-Famatinian orogen (Dalla Salda et al. 1992; Dalziel et al. 1994) is not accurate in view of the available geological data and the new gravity evidence presented here for the Central Andes. On the contrary, our model favours a close palaeogeographic relationship between Laurentia and the Argentinean Precordillera as a minor terrane. The recognition of this singular origin is also supported by strong palaeontological, stratigraphic (Astini et al. 1995) and palaeomagnetic evidence (Niocaill et al. 1997). Some recent speculation about the Ordovician (Arenigian-Llanvirnian) K-bentonite deposit are interesting. Their stratigraphic distribution shows great similarities to sequences outcropping in Baltica, Central Appalachians and the Argentine Precordillera (Bergström 1989; Bergström et al. 1996).

The balance of the evidence allows depiction of a progressive drifting and accretion of the Precordillera-Mejillonia terrane (PM) detached from Laurentia. These allochthonous slivers with Grenville basement are interpreted here to have formed a very large landmass consisting of at least two definable blocks: the Precordillera and the Mejillonia (see Fig. 11). Their amalgamation with pre-Gondwana (~450 Ma) was preceded by:

1. An arc-related magmatism along the Famatinian margin of CABA (Figs. 9, 10)
2. An extensive back-arc magmatism (Fig. 10)
3. The consolidation of the mobile zone by folding, thrusting and obduction of ophiolites and mafic volcanites in the Argentinean Precordillera and southern Puna

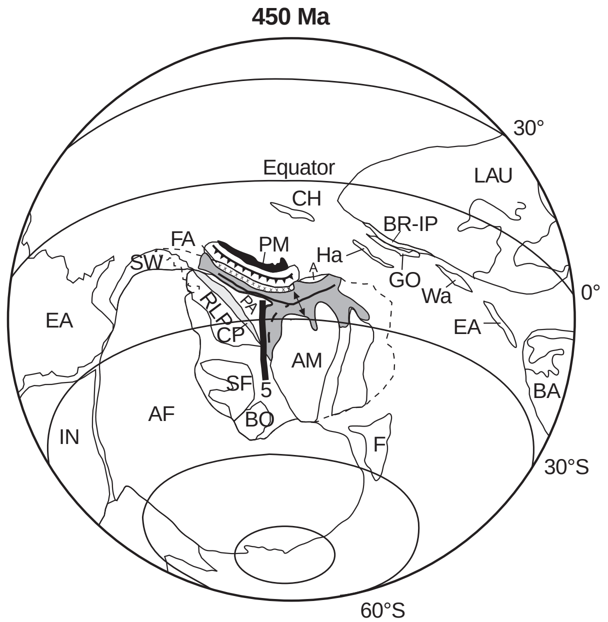


Fig. 9 Late Ordovician–Early Silurian (ca. 450 Ma) palaeogeographic reconstruction. The African continent and East Gondwana assemblage as in Torsvik et al. (1996). Laurentia and Baltica positions modified from Torsvik et al. (1996) and Dalziel (1997). The agglomeration of Amazonia (*AM*), Pampia (*PA*), Rio de la Plata (*RLP*), CABA and SW terranes in based on geological evidence (see text). The Precordillera-Mejillonia (*PM*) terrane, involving the subduction zone and the Famatinian magmatic arc (*FA*) is in *light grey*. Ordovician back-arc and foreland basins. *A* Arequipa massif; *EA* East Avalonia; *AF* Africa; *5* Aconquija-Paraguay lineament

Discussion of the ensialic pre-Gondwana consolidation at the Pacific margin

According to previous tectonic interpretations, the assemblage of the pre-Gondwana lands on the Pannotia margin resulted from the complex movements of individual terranes; however, their sutures must be everywhere parallel to the present trend of the orogenic belt. With this concept in mind it is possible to draw the following scenario:

1. The Río de la Plata craton was amalgamated to the Pampia craton during the interval 750–650 Ma. The

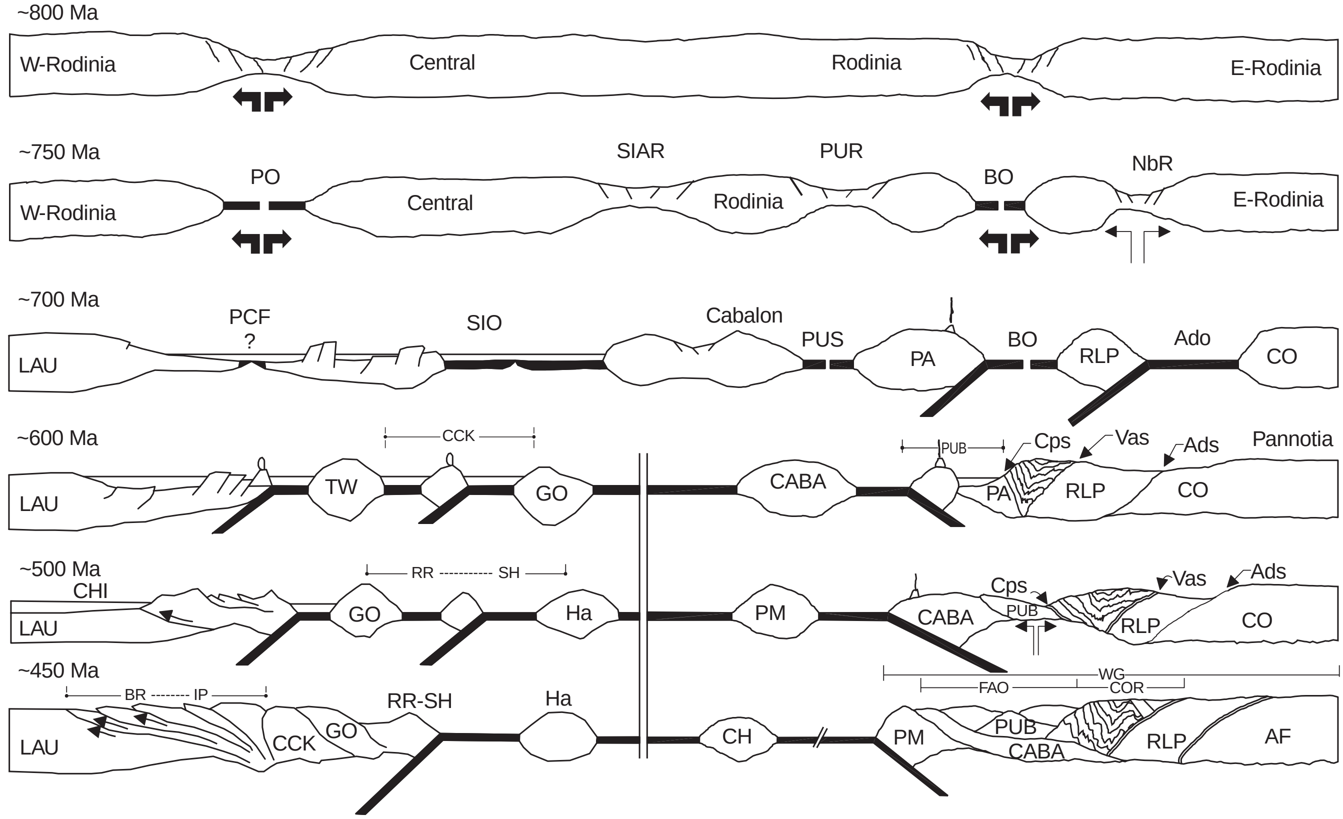


Fig. 10 Interpretative sequence of events during the break-up of the Rodinia supercontinent. The limit between West and East Rodinia is indicated according to the palaeogeographic reconstruction at 777 Ma proposed by Torsvik et al. (1996). West Rodinia includes Australia, East Antarctica, India, Madagascar and Budelkhand terranes. Central Rodinia includes Laurentia, Siberia, North China terranes. East Rodinia includes Pampia, Rio de la Plata, Amazonia, Congo, West Africa Baltica, Kalahari, Sao Francisco and SW terranes. *SIAR* South Iapetus rift; *PO* Proto-Pacific Ocean; *PUR* Puncoviscana rift; *BO* Brasiliedes Ocean; *NbR* Nosib rift; *PCF* Pre-Catoctin Formation; *SiO* South Iapetus Ocean; *CABALON* Cuyania, Belen, Antofalla, Arequipa, Tawson, Goochaland and Hatteras terranes; *PUS* Puncoviscana Sea; *PA* Pampia terrane; *RLP* Rio de la Plata terrane; *Ado* Adamastor Ocean; *CO* Congo terrane; *TW* Tawson terrane; *CCK* Charlotte-Carolina-Kioke belt; *GO* Goochaland terrane; *HA* Hatteras terrane; *CABA* Cuyania, Antofall, Belen, Arequipa terranes; *PUB* Puncoviscana belt; *Cps* Córdoba-Paraguay suture; *Vas* Vacacai suture; Ados Adamastor suture; *CHI* Chilhowee Formation; *RR-SH* Roanoke Rapids-Spring Hope terranes; *PM* Precordillera-Mejillonia terrane; *BR-IP* Eastern Blue Ridge-Inner Piedmont; *CH* Chilean terrane; *FAO* Famatinian orogene; *COR* Córdoba range; *WG* West Gondwanaland; *AF* Africa terrane

convergent evolution of the Córdoba-Paraguay belts was probably controlled by west subduction, into a configuration similar to the one proposed by Ramos (1988, 1991). The high metamorphism along the edge of the anatectic migmatite nuclei in the Córdoba ranges decreases until the Colorado River at the Patagonia border. It peaked between 730 and 650 Ma (Sureda 1978; Linares et al. 1980; Párica 1986), marking the collisional event. After these episodes a younger magmatic and metamorphic edge was developed along the eastern border of the consolidated Pampia–Rio de la Plata massif. The volcanites and related rocks with associated tungsten ore deposits in Sierra del Morro, San Luis (Hack et al. 1991; Delakowitz et al. 1991), are interpreted here as having been generated during a similar time span and geodynamical conditions as the Puncoviscana Formation in Salta and Jujuy.

2. The Paraguay-Araguay basin (3 in Fig. 8) and the Tucavaca-Puncoviscana basin were deformed in the Pan-African-Brasilian orogeny (530–520 Ma). The arguments presented previously imply that the Pampia-Río de la Plata craton collided with the Amazonia before the collision between CABA and the Amazonia-Pampia craton. It is possible that the Candelaria terrane (9 in Fig. 11), with crustal rocks of middle to high metamorphism and penetrative deformation (Willner 1990), forms part of the Paraguay-Araguay belt and not of the Puncoviscana belt as currently assumed. It is also noteworthy that the Aconquija-Paraguay lineament (4 in Fig. 11) crosses the South American continent in a position coincident with the northeast–southwest trend of the belt (5 in Fig. 9). The development of this lineament persisted throughout geological time and appears to have exerted a strong influence on the location and development of the island arcs and volcanogenic regimes relative to the Puncoviscana belt. This assumption is in agreement with the geophysical findings. Also, the geological record suggests

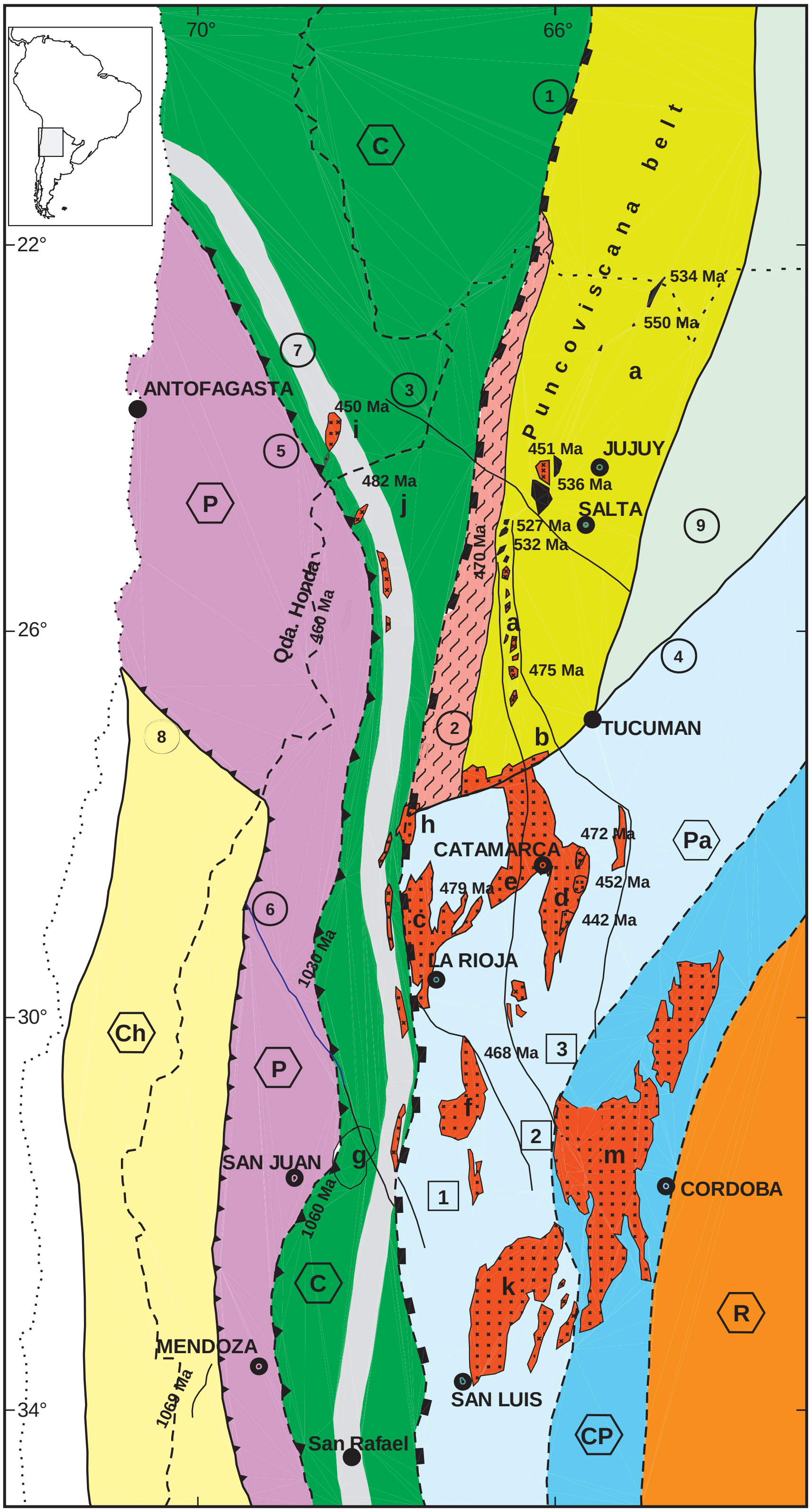


Fig. 11 Palaeogeographic interpretation map of the Central Andes and adjacent regions shows the distribution of terranes and suture zones. The Famatinian arc (*light grey*) has been inferred from gravity interpretation. *Numbers in circles: 1* Tilcarian suture (Late Precambrian); *2* Eastern Puna Mylonite zone; *3* Calama-Olacapato-Toro lineament; *4* Aconquija lineament; *5* Ocloyic suture (Late Ordovician); *6* Valle Fertil lineament; *7* Famatinian magmatic arc; *8* Valle Ancho lineament; *9* Candelaria terrane: *a* Cordillera Oriental and Cumbres Calchaquies morphostructural provinces; *b* Aconquija ranges; *c* Ancasti ranges; *d* Velasco ranges; *e* Ambato ranges; *f* De los Llanos ranges (includes Chepes and Ulapes ranges); *g* Pie de Palo ranges; *h* Fiambala ranges; *i* Cordón de Lila ranges; *j* Macón, Taca-Taca, Arita, Archibarca, Antofalla granitoids; *k* San Luis ranges; *m* Córdoba ranges. *Numbers in squares: 1* Amphibolite–biotite granitoids; *2* Aluminium–silicate granitoids; *3* Epidote micaceous granitoids. *Letters in circles: C* Cuyania-Antofalla-Belen-Arequipa (CABA) terrane; *P* Precordillera-Mejillonia terrane; *R* Rio de la Plata craton; *Pa* Pampia terrane; *Ch* Chilenia terrane; *Cp* Córdoba-Paraguay arc

different rates of CABA convergence and/or amalgamation on the two sides, northward and southward of the Aconquija-Paraguay lineament. The northern portion is associated with a variety of gravity anomalies in connection with an island-arc development on a very thin ensialic basement or in oceanic crust. The southern portion appears to be associated with a magmatic arc developed on sialic basement (Pampia craton), which led to an extensive continental suture after the CABA amalgamation.

Geological evidence for this assemblage comes from granitoid emplacement into the western Sierras Pampeanas between 570 and 520 Ma (Rapela et al. 1990; Rapela and Pankhurst 1996; Sato et al. 1996).

3. A convergent event on the western margin of the CABA terrane is indicated in the interval 500–439 Ma by the subduction–obduction of ophiolites, as well as thrusting and folding of sedimentary rocks (Calingasta Valley; Kay et al. 1984), which has been referred to here as the accretion of the Precordillera-Mejillonia terrane. Geological evidence indicates a very important dynamical regime of more or less continuous convergence. The magnitude of this process is documented by a well-developed Late Ordovician volcanic and plutonic belt (7 in Fig. 11) known as the Famatinian magmatic arc (Aceñolaza and Toselli 1989). This magmatic arc, related to an A-type eastward subduction, originated on an attenuate CABA continental crust. A plutonic belt with peraluminous affinity was emplaced at a similar time in the back arc, presently known as the western Pampean ranges (see Fig. 11; Rapella et al. 1990; Toselli 1992). This plutonism is also very well documented in the Puna and the Eastern Cordillera, where it is associated with continuous gravity anomalies (2 in Fig. 5) and includes areas of concentrated mineral resources.
4. A similar A-type eastward subduction was responsible for the final assembly of the proto-Gondwana terranes by amalgamation of the Chilenia terrane in the Late Paleozoic (Ramos et al. 1984). This collision marks the Chañic diastrophic phase (Early Carboniferous), which led to a new Pangea and to the start of the Gondwania cycles.

Acknowledgements The work of the Argentine authors was supported by CONICET, Argentina grant PID no. 3364900-92 and 3648/92, and CIUNSa project 646/96. The gravity survey in the Central Andes is part of field work of the Collaborative Research Center 267 (projects D3C6) which is financially supported by "Deutsche Forschungsgemeinschaft" (DFG) and "Freie Universität" Berlin. This research is a contribution to IGCP 345 "Laurentia-Gondwana connection before Pangea". The authors are very grateful to C. D. Reuther, K. Hoernle and an anonymous referee for critical reading of the manuscript.

References

Aceñolaza F (1978) El Paleozoico inferior de Argentina según sus trazas fósiles. Ameghiniana 15:15–64

Aceñolaza FG, Durand F (1986) Upper Precambrian–Lower Cambrian biota from the Northeast of Argentina. Geol Mag 123:367–375

Aceñolaza FG, Toselli AJ (1989) El sistema de Famatina, Argentina: su interpretación como orógeno de margen continental activo. Fifth Congr Geol Chileno, pp A55–A67

Almeida FFM, Hasui Y, Brito Neves BB (1976) The upper Precambrian of South America. Bol Inst Geosci Univ Sao Pablo Brasil 7:45–80

Astini RA, Benedetto JL, Vaccari NE (1995) The early Paleozoic evolution of the Argentine Precordillera as a Laurentia rifted, drifted and collided terrane: a geodynamic model. Geol Soc Am Bull 107:253–273

Astini RA, Ramos V, Benedetto JL, Vaccari NE, Cañas FL (1996) La Precordillera: Un terreno exótico a Gondwana. Thirteenth Congr Geol Argentina V:293–324

Bachmann G, Grauert B, Kramm U, Lork A, Miller H (1987) El magmatismo Cámbrico medio Cámbrico superior en el basamento del noroeste argentino: investigaciones isotópicas y geocronológicas sobre los granitoides de los complejos intrusivos Santa Rosa de Tastil y Cañani. Tenth Congr Geol Argentina 4:125–127

Baldis B (1989) Autochthony of South American Eopaleozoic platforms. Int Geol Congr Washington 1:77–78

Benedetto JL (1993) Hipótesis de la aloctonía de la Precordillera Argentina: un test estratigráfico y bioestratigráfico. Twelfth Congr Geol Argentina 3:375–384

Bengtson S, Flechter T (1983) The oldest sequence of skeletal fossils in the lower Cambrian of southeastern Newfoundland. Can J Earth Sci 20:525–536

Bergströn SM (1989) Use of graphic correlation for assessing event-stratigraphic significance and trans-Atlantic relationships of Ordovician K-Bentonites Eesti NSV Tead Akaeenia Toimetised. Geologia 3382:55–59

Bergström SM, Huff WD, Kolata DR, Kreleler MPS, Cingolani C, Astini R (1996) Lower and middle Ordovician K-Bentonites in the Precordillera of Argentina: a progress report. Thirteenth Congr Geol Argentina 5:481–490

Bevier ML (1989) Preliminary U–Pb geochronologic results for igneous and metamorphic rocks, New Brunswick. In: Abbott (ed) 14th Annu Rev Activ Inf Cir 89:190–194

Black WW (1978) Chemical characteristics and Rb/Sr ages of meta volcanics from the Carolina slate belt of North Carolina. Geol Soc Am Abstr Progr 10:162–163

Bond G, Nickeson PA, Komin M (1984) Breakup of a supercontinent between 625 Ma and 555 Ma: new evidence and implications for continental histories. Earth Planet Sci Lett 70:325–345

Boltin WR, Stoddard EF (1987) Transition from Eastern slate belt to Raleigh belt in the Hollister Quadrangle, North Carolina: Southeastern Geol 27:185–205

Bradshow TK, Hawkesworth CJ, Gallagher K (1993) Basaltic volcanism in the Southern Basin and Range: no role for mantle plume. Earth Planet Sci Lett 116:45–62

Brockmann C, Castaños A, Suarez R, Tomasi P (1972) Estudio geológico de la Cordillera Oriental de los Andes en la zona central de Bolivia (Región del Chapare). Soc Gol Bo 18:3–36

Caminos R (1979) Cordillera frontal. In: Turner JCM (ed) Geología Regional Argentina. Acad Nac Ciencias Córdoba Argentina 1:397–453

Coira B, Manca N, Chayle WE (1990) Registros volcánicos en la Formación Puncoviscana. Serie Correlación Geológica, Tucumán, Argentina 4:53–60

Criado Roque P (1972) El bloque de San Rafael. In: Leanza (ed) Geología Regional Argentina. Acad Nac Ciencias Córdoba Argentina 1:237–287

Crimes TP, Anderson NM (1985) Trace fossils from the Late Precambrian–early Cambrian strata of southeastern Newfounland (Canada): temporal and environmental implications. J Paleontol 59:310–343

Condie KC (1990) Plate tectonics and crustal evolution, 3rd edn. Pergamon Press, New York, p 476

D'Agrella-Filho MS, Trinidade RF, Siqueira R, Ponte-Neto CF, Pacca IG (1998) Paleomagnetic constraints on Rodinia Supercontinent: implications for its Neoproterozoic break-up and formation of Gondwana. Int Geol Rev 40:171–188

Dalla Salda L, Cingolani C, Varela R (1992) Early Paleozoic orogenic belt of the Andes in southwestern South America: result of Laurentia-Gondwana collision? Geology 20:617–620

Dalla Salda L, Cingolani C, Varela R (1993) A pre-Carboniferous tectonic model in the evolution of southern South America. Comptes Renddus. XII ICC-P V.1:371–384

Dallmeyer RD (1989) Contrasting accreted terranes in the southern Appalachian orogen basement beneath the Atlantic and Gulf coastal plains, and west African orogens. Precambrian Res 42: 387–409

Dalziel IWD (1991) Pacific margins of Laurentia and East Antarctic–Australia as a conjugate rift pair: evidence and implications for an Eocambrian supercontinent. Geology 19: 598–601

Dalziel IWD (1997) Neoproterozoic–Paleozoic geography and tectonics: review hypothesis environmental speculation. Geol Soc Am Bull 109: 17–42

Dalziel IWD, Dalla Salda L, Gahagan L (1994) Paleozoic Laurentia-Gondwana interaction and the origin of the Appalachian-Andean Mountain system. Geol Soc Am Bull 106: 243–252

Damm KW, Pichoviak S, Harmon R, Todt W, Kelley S, Omarini R, Niemeyer H (1991) Premesozoic evolution of the central Andes: the basement revisited. In: Kay S, Rapela W (eds) Plutonism from Antarctic to Alaska. Geol Soc Am Spec Pap 241: 101–126

Delakowitz B, Höll R, Brodtkorb MK, Brodtkob A (1991) Geología y génesis de yacimientos scheelíticos en la Sierra del Morro oeste-Provincia de San Luis. In: Brodtkob MK (ed) Geología de yacimientos de wolframio de las provincias de San Luis y Córdoba. Rev Inst Recur Mineral, Univ Nac La Plata, Argentina V (1): 49–96

Dennis AJ, Shervais JW (1991) Arc-rifting of the Carolina terrane in the north western South Carolina. Geology 19: 226–229

Durand RF (1994) Sintesis sobre el conocimiento icnológico del basamento Precámbrico,Cámbrico del noroeste argentino. Acta Geol Leopoldensia 17: 733–746

Edwards CM, Menzies MA, Thirlwall MF, Morris JD, Leeman W, Harmon R (1994) The transition to potassic alkaline volcanism in island arcs: the ringgit-Beser complex, East Java, Indonesia. J Petrol 25: 1557–1595

Fitton JG, Dunlop HM (1985) The Cameroon line, West Africa, and its bearing on the origin of oceanic and continental alkali basalt. Earth Planet Sci Lett 72: 23–38

Foley SF,Venturelli G, Green D, Toscani L (1987) The ultrapotassic rock: characteristics, classification, and constraints for petrogenetic models. Earth Sci Res 24: 81–134

Fraser KJ, Hawkesworth CJ, Erlank AJ, Mitchell RH, Scott-Smith BH (1985) Sr, Nd and Pb isotope and minor element geochemistry of lamproites and kimberlites. Earth Planet Sci Lett 76: 57–70

Galliski MA (1983) Distrito minero El Quemado, departamento La Poma y Cachi, provincia de Salta I: El basamento del tramo septentrional de la Sierra de Cachi. Asoc Geol Argentina 38: 209–224

Galliski MA, Miller C (1989) Petrogenesis de las trondhjemitas de Cachi: condicionamientos impuestos por elementos de tierras raras e implicancias tectónicas. Reunión de transectas America del Sur, Mar del Plata Argentina, pp 58–62

Galliski MA, Toselli AJ, Saavedra J (1990) Petrology and geochemistry of the Cachi high alumina trondhjemites, northwestern Argentina. In: Kay S, Rapela C (eds) The Plutonism from Antarctic to Alaska. Geol Soc Am Spec Pap 241: 91–101

Gangui A, Götze HJ (1996) The deep structures of the Northern Argentina: constraints from 2D seismic data 3D gravity modelling. Thirteenth Congr Geol Argentina 5: 545–565

Gibson GG, Teeter SA, Fedonkin MA (1984) Ediacarian fossils from the Carolina slate belt Standly Country, North Carolina. Geology 12: 387–390

Goldsmith R, Secor DT Jr (1993) Proterozoic rocks in accreted terrane in the eastern United States. Geol Soc Am C2: 422–439

Gonzalez Bonorino G, Gonzalez Bonorino F (1991) Precordillera de Cuyo y Cordillera Frontal en el Paleozoico temprano: terrenos bajo sospecha de ser autóctonos. Rev Geol Chile 18: 97–107

Gonzalez Bonorino G, Llambias E (1996) Geologic and Paleogeographic development of southern South America (excluding Brazil) in the Proterozoic and Early Paleozoic In: Moullade M, Nairn AEM (eds) The Phanerozoic geology of the world. Elsevier, Amsterdam, pp 265–338

Götze H-J, Kirchner A (1997) Gravity field at the South American active margin (20° to 29° S). J South Am Earth Sci 10: 179–188

Götze H, Schmidt S, Strunk S (1988) Central Andean gravity field and its relation to crustal structures. In: Bahlburg H, Breitkreuz C, Giese P (eds) The southern Central Andes. Lecture Notes Earth Sci 17: 199–209

Götze HJ, Lahmeyer B, Schmidt S, Strunk S (1994) The lithospheric structure of the Central Andes (20–26 S) as inferred from interpretation of regional gravity. In: Reutter K, Scheuber E, Wigger P (eds) Tectonics of the southern Central Andes. Springer, Berlin Heidelberg New York, pp 7–23

Götze H-J and the MIGRA group (1996) Group updates the gravity data base in the Central Andes (20–29° S). EOS Trans Am Geophys Union Electronic Suppl, 5 pages. http://www.agu.org/eoselec/95189e.html

Goodge J, Walker N, Hansen V (1993) Neoproterozoic Cambrian basement involved orogenesis within the Antarctic margin of Gondwana. Geology 21: 37–40

Gradstein FM, Ogg J (1996) A Phanerozoic time scale. Episodes 19: 3–5

Hack M, Brodtkorb MK, Höll R, Brodtkorb A (1991) Geología y consideraciones genéticas de los yacimientos scheelíticos entre el dique La Florida y Pampa del Tamboreo, provincia San Luis. In: Brodtkorb MK (ed) Geología de yacimientos de wolframio de las provincias de San Luis y Córdoba, Argentina. Inst Recuros Naturales Univ Nac La Plata Argentina 1: 113–152

Hatcher RD Jr (1989) Tectonic synthesis of the US Appalachians. In: Hatcher RD, Thomas WA, Viele GW (eds) The Appalachian-Ouachita orogen in the United States. Geol Soc Am Geol North Am VF (2): 511–535

Hoffmann PF (1991) Did the breakout of Laurentia turn Gondwanaland inside-out? Science 252: 1409–1412

Horton JW, Stoddard EF (1986) The Roanoke Rapids complex of the Eastern slate belt, Halifax and Northampton countries, North Carolina. In: Neathery TL (ed) Southeastern section of the Geological Society of America. Geol Soc Am Centennial Field Guide 6: 217–222

Horton JW, Drake A, Rankin D (1989) Tectonostratigraphic terranes and theirs Paleozoic boundaries in the central and southern Appalachians. In: Dallmeyer RD (ed) Terranes in the circum-Atlantic Paleozoic Orogens. Geol Soc Am Spec Pap 230

Jêzek P (1986) Petrographie und Fazies der Puncoviscana Formation einer turbiditischen Folge im Jungprä kambrium und Unterkambrium Nordwest Argentiniens. PhD thesis, Wilhelms Univ, Münster, Germany, pp 1–136

Jêzek P (1990) Análisis sedimentológico de la Formación Puncoviscan entre Tucumán y Salta. In: Aceñolaza F, Miller H, Toselli AJ (eds) El Ciclo Pampeano en el noroeste argentino. Serie Correlación Geol 4: 9–36

Kay SM, Ramos VA, Kay R (1984) Elementos mayoritarios y trazas de vulcanitas ordovícicas en la Precordillera occidental. Basaltos de rift oceánicos tempranos (?) próximo al margen continental. Ninth Congr Geol Argentina 2: 48–65

Kamo SL, Gower CF, Krogh TE (1989) Birthday for the Iapetus ocean? A precise U–Pb zircon and baddeleyite age from the long Range dykes, southeast Labrador. Geology 17: 602–605

Keppie DJ (1989) Northern Appalachian terranes and their accretionary history. In: Dallmeyer RD (ed) Terranes in the Circum-Atlantic Paleozoic orogens. Geol Soc Am Spec Pap 230: 159–193

Kilmurray JO, Merodio JC, Rapela CW (1974) Las metamorfitas cordieríticas del área Estación Incahuasi- Santa Rosa de Tastil, Provincia de Salta: rasgos petrológicos y geoquímicos. AsocGeol Argentina 29: 425–442

Kozuch M, Heatherington AL, Mueller PA, Offield TW, Kappen R, Klein TL (1992) Magmatism in the Carolina terrane: isotopic evidence for the Grenville-age source for the Proterozoic volcanics and a mantle source for the Silurian Concord syenite. Geol Soc Am Abstr Progr 24-7:217

Krogh T, Strong DF, Papezik VS (1983) Precise Y–Pb ages of zircons from volcanic and plutonic units in the Avalon Peninsula. Geol Soc Am Abstr Progr 13:135

Kumarapeli PS (1993) A plume-generated segment of the rifted margin of Laurentia, southern Canadian Appalachians, seen through a completed Wilson cycle.Tectonophysics 219:47–55

Kumarapeli S, Seymour St. K, Pintson H, Haselgren E (1988) Volcanism on the passive margin of Laurentia: an early Paleozoic analogue of Cretaceous volcanism on the northeastern America margin. J Can Earth Sci 25:1824–1833

Linares E, Turner J (1976) Comarcas con rocas de edad precámbrica de la República Argentina, sobre la base de dataciones radimétricas. Sixth Congr Geol Argentina 1:25–32

Linares E, Llambias E, Latorre C (1980) Geología de la provincia de La Pampa, Argentina, sobre la base de dataciones radimétricas. Sixth Congr Geol Argentina 1:25–32

Lork A, Miller H, Kramm U (1990) U–Pb zircon and monazite ages of the Angostura granite and the orogenic history of the northwest Argentine Basement. J South Am Earth Sci 2:147–153

Lucassen F, Leerenz S, Franz G, Viramonte J, Mentzger K (1998) Metamorphism isotopic age, and chemistry of Lower Cretaceous xenoliths from Cretaceous Salta Rift Argentina: Probing the Brazilian Shield. Contrib Mineral Petrol (in press)

Lucero Michaut HN (1979) Sierras Pampeanas del norte de Córdoba, sur de Santiago del Estero, borde oriental de Catamarca y ángulo sudeste de Tucumán. In: Geología Regional Argentina. Acad Nac Ciencias Córdoba Argentina 1:294–347

Maher HD, Palmer AR, Secor DT, Snoke AW (1981) New turbidite locality in the Piedmont of South Carolina and its regional implications. Geology 9:34–36

McKerrow WS, Scotese CR, Brasier MD (1992) Early Cambrian continental reconstructions. J Geol Soc Lond 5:599–606

McWillians MO (1981) Paleomagnetism and Precambrian tectonic evolution of Gondwana. In: Kroner (ed) Precambrian plate tectonics. Elsevier, Amsterdam, pp 649–687

Milton DJ (1984) Revision of the Abemarle Group, North Carolina. US Geol Surv Bull 1537:69–72

Milton DJ, Reinhardt J (1980) Turbidites in the Albemarle Group, Carolina slate belt, Standly Country, North Carolina. Geol Soc Am Abstr Progr 12:202

Mon R, Hongn F (1996) Estructura del basamento proterozoico y paleozoico inferior del norte argentino. Rev AsocGeol Argentina 51:3–14

Moore EM (1991) Southwest US East Antarctic (SWEAT) connection: a hypothesis. Geology 5:425–428

Muller PD, Chapin DA (1984) Tectonic evolution of the Baltimore gneiss anticlines, Maryland. Geol Soc Am Spec Pap 194:127–148

Murphy JB, Keppie JD, Nance RD, Dostal J (1990) The Avalon composite terrane of Nova Scotia. In: Strachan RA, Taylor GK (eds) Avalonian and Cadomian geology of the North Atlantic. Blackie, London, pp 195–214

Mutti E, Normark WR (1987) Comparing examples of modern and ancient turbidites systems: problems and concept. In: Leggett J, Zuffa G (eds) Marine clastic sedimentology. Graham and Trotman, London, pp 1–37

Niocaill M, Van der Plujim V, Van der Voo R (1997) Ordovician paleogeography and evolution of Iapetus Ocean. Geology 25:159–162

O'Connor E, Welde D (1986) Recognition of Eocambrian progenic cycle in SW Brazil and SE Bolivia. Zentralbl Geol Paläontol 1441–1456

Omarini RH (1983) Caracterización litológica diferenciación y génesis de la Formación Puncoviscana entre el Valle de Lerma y la Faja Eruptiva de la Puna. PhD thesis, Univ Salta, Argentina. pp1–202

Omarini RH, Baldis BAJ (1984) Sedimentología y mecanismos deposicionales de la Formación Puncoviscana (Grupo Lerma, Precámbrico-Cámbrico) del norte argentino. Ninth Congr Geol Argentina 1:383–398

Omarini RH, Götze H J (1991) Central Andes Transect, Nazca Plate to Chaco Plains, southwestern Pacific Ocean, northern Chile and northern Argentina. Copublished by Inter-Union Comm Lithos and Am Geophys Union, Washington, 30 pp

Omarini RH, Sureda RJ (1993) Evolución geodinámica y configuración paelogeográfica en los Andes Centrales del Proterozoico superior al Paleozoico inferior: modelos, alternativas y problemas. Twelfth Congr Geol Argentina 3:291–308

Omarini RH, Sureda RJ (1994) El basamento centroandino y sus cuencas marginales entre el rift Irúyico (515 Ma) y la collisión Oclóyica (435 Ma). Seventh Congr Geol Chileno 1:491–498

Omarini R, Aparicio Yague A, Pichoviak S,Viramonte J, Damm K, Garcia Cacho L (1987a) Santa Rosa de Tastil Granitic Complex, Salta, Argentina: an unusual "S" type granite. Tenth Congr Geol Argentina 5:119–121

Omarini R, Aparicio Yague A, Viramonte J (1987b) Cañani granitic complex, Salta, Argentina: geochemical and petrological approach. Tenth Congr Geol Argentina 4:122–124

Omarini R, Torres G, Moya L (1996) El stock Tipayoc: genesis magmática en un arco de islas del Cámbrico Inferior en el noroeste de Argentina. Thirteenth Congr Geol Argentina 5:545–561

Párica PD (1986) Petrología y geocronología del sector central de la sierra de Lonco Vaca, La Pampa. Rev AsocGeol Argentina T41:270–290

Pearce JA (1982) Trace element characteristics of lavas from destructive plate boundaries. In: Thorpe RS (ed) Andesites: orogenics, andesites and related rock. Willy Interscience, New York, pp 525–548

Pearce JA (1983) Role of the subcontinental lithosphere in magma genesis at active continental margins. In: Hawkesworth C, Morry M (eds) Continental basalts and mantle xenoliths. Shiva, Nantwich, pp 230–249

Pe-Piper G, Piper DJW (1989) The upper Hadrynian Jeffers Group, Cobequid Highlands, Avalon zone of Nova Scotia: a back-arc volcanic complex. Geol Soc Am Bull 101:364–376

Piper J (1982) The Precambrian paleomagnetic record: case for the Precambrian supercontinent. Earth Planet Sci Lett 59:61–89

Powell CMc, Li ZX, McElhinny MW, Meert JG, Park JK (1994) Paleomagnetic constraints on timing of the Neoproterozoic breakup of Rodinia and the Cambrian formation of the Gondwana. Geology 22:889–892

Prave AR (1996) Tale of three cratons: tectonostratigraphic anatomy of the Damara orogen in northwestern Namibia and assembly of Gondwana. Geology 24:1115–1118

Ramos VA (1988) Late Proterozoic–Early Paleozoic of South America: a collisional history. Episodes 11:168–175

Ramos VA (1991) Los ambientes tectónicos de los distritos wolframíferos de las Sierras Pampeanas. In: Brodtkorb M (ed) Geología de los yacimientos de wolframio de la provincias de San Luis y Córdoba. Rev Inst Recursos Mineral Univ Nac La Plata 5:185–196

Ramos VA, Jordan T, Allmendinger RW, Kay SM, Cortés JM, Palma MA (1984) Chilenia un terreno alóctono en la evolución paleozoica de los Andes Centrales. Ninth Congr Geol Argentina T2:84–106

Rapela C, Pankhurst R (1996) The Cambrian plutonism of the Cordoba ranges: pre Famatinian subduction? and crustal melting. Thirteenth Congr Geol Argentina T(5): 471–481

Rapela C, Toselli A, Heaman L, Saavedra J (1990) Granite plutonism of the Sierras Pampeanas: an inner cordilleran Paleozoic arc in the southern Andes. In: Kay MS, Rapela CW (eds) Plutonism from Antarctica to Alaska. Geol Soc Am Bull Spec Pap 241:77–91

Rock NMS (1991) Lamprophyres. Blackie, Glasgow

Roger JJW (1982) Criteria for recognize environments of formation of volcanic suites: application of these criteria to volcanic suites in the Carolina slate belt. In: Bearce D, Black WW, Kish SA, Tull JF (eds) Tectonics studies in the Talladega and Carolina slate belts, southern Appalachian orogen. Geol Soc Am Spec Pap 191:99–107

Ross RJ (1991) Tectonic setting in the Windermere Supergroup: the continental perspective. Geology 19:1125–1128

Rossi JN, Toselli AJ, Durand FR (1992) Metamorfismo de baja presión, su relación con eldesarrollo de la cuenca Puncoviscana, plutonismo y regimen tectónico. Argentina. Estudios Geol 48:279–287

Rowell AJ, Rees MN, Duebendorfer EM, Wan Schmus WR, Wallin ET, Smith EI (1993) An active Neoproterozoic margin: evidence from the Skelton Glacier area, Transantarctic Mountains. J Geol Soc Lond: 150

Saavedra J, Toselli A, Rossi de Toselli JN, Rapela C (1987) The role of tectonism and fractional crystallization in the origin of lower Paleozoic epidote-bearing granitoids, NW Argentina. Geology 15:709–713

Sato AM, Ortiz Suarez A, Llambias EJ, Cavarozzi CE, Sanchez V, Varela R, Prozzi C (1996) Los plutones pre-Oclóyicos del sur de las sierras de San Luis: Arco magmático al inicio del ciclo famatiniano. Twelfth Congr Geol Argentina T5:259–272

Schön C, Miller H (1990) Desarrollo bifásico del complejo intrusivo al SW de Cachi, provincia de Salta, NW argentino. Eleventh Congr Geol Argentina T1:145–149

Secor DT Jr, Murray DP, Glover L (1989) Geology of the Avalonian rocks. In: Rankin DW et al. (eds) The Appalachian-Ouachita orogen in the United States. Geol Soc Am Geol North Am F-2:57–85

Seilacher A, Pflüger F (1992) Trace fossils from the late Proterozoic of North Carolina: early conquest of deep-sea bottoms. Paleontol Soc Spec Publ 6:265 (NAPC V abstr vol)

Seilacher A, Pflüger F (1994) From biomats to benthic agriculture: a biohistoric revolution. In: Krumbein WE, Paterson DM, Stal LJ (eds) Biostabilization of sediments. BIS, Oldemburg, pp 97–105

Seider VM (1978) A chemically bimodal calc-alkalic suite of volcanic rocks, Carolina volcanic slate belt, central North Carolina. Southeast Geol 19:241–265

Seymour KSt, Kumarapeli PSt (1995) Geochemistry of the Grenville Dyke Swarm: role of plume source mantle in magma genesis. Contrib Mineral Petrol 120:29–41

Stein M, Hoffmann AW (1992) Fossil plume head beneath the Arabian lithosphere? Earth Planet Sci Lett 114:193–209

Stewart JH (1972) Initial deposits of the Cordilleran geosyncline: evidence of late Precambrian (<850 Ma.) continental separation. Geol Soc Am Bull 83:1345–1360

Storey BC, Alabaster T, Macdonal DIM, Pankhurt RJ, Dalziel IWD (1992) Upper Proterozoic rift-related rocks in the Pensacola Mountains, Antarctica: precursors to supercontinent breakup? Tectonics 11:1392–1405

Storey BC (1993) The changing face of late Precambrian and early Paleozoic reconstructions. J Geol Soc Lond 5:665–668

Strunk S (1990) Analyse und Interpretation des Schwerefeldes des aktiven Kontinentalrandes der Zentralen Anden, (20–26 S) Berl Geowiss Abh 17:1–135

Sureda RJ (1978) Las vetas de plomo, plata y zinc del distrito minero El Guaico en la Provincia de Córdoba, República Argentina. Rev Asoc Geol Argentina 33:299–324

Sureda RJ, Avila Salinas W, Marquillas RA (1989) La Provincia Metalogénica del Bermejo: un análisis preliminar de sus depósitos minerales en Argentina y Boliva. In: Depoósitos Minerales del Cretácico de America Latina. Contr PICG-342 Parte B: 25–48

Thomas A (1977) Evolution of the Appalachian-Ouchita salients and recesses from reentrants and promontories in the continental margin. Am J Sci 277:1233–1278

Thompson RN, Morrison MA, Hendry GL, Parry SJ (1984) An assessment of relative roles of crust and mantle in magma genesis: an elemental approach. Phil Trans R Soc Lond 310:549–590

Torsvik TH, Smethurst MA, Meert JG, Van der Voo R, Mckerrow WS, Brasier MD, Sturt BA,Walderhaug HJ (1996) Continental break-up and collision in the Neoproterozoic and Paleozoic: a tale of Baltica and Laurentia. Earth Sci Rev 40:229–258

Toselli AJ (1992) El magmatismo del noroeste argentino. Serie Correlación Geol Univ Nac Tucumán Argentina 8:1–243

Turner JCM (1960) Estratigrafía de la Sierra de Santa Victoria. Acad Nac Ciencias Córdoba Argentina Bol 49:163–196

Turner JCM (1961) Estratigrafía del Nevado de Cachi y sector oeste (Salta). Acta Geol Lilloana 3:191–226

Unrug R (1996) The assembly of Gondwanaland. Episodes V.19:11–20

Unrug R (1997) Rodinia to Gondwana: the geodynamic map of Gondwana supercontinent assembly. Geol Soc Am Today 7:1–7

Voo van der R (1988) Paleozoic paleogeography of North America, Gondwana and intervening displaced terranes: comparisons of paleomagnetism with paleoclimatology and biogeographical patterns. Geol Soc Am Bull 100:311–324

Wasteneys HA, Clark AH, Farrar E, Langridge RJ (1995) Grenvillian granulite-facies metamorphism in the Arequipa Massif, Peru: a Laurentia-Gondwana link. Earth Planet Sci Lett 132:63–73

Weaver B (1991) The origin of ocean island basalt end-member compositions: trace element and isotopic contraints. Earth Planet Sci Lett 104:381–397

Wehr F, Glover L (1985) Stratigraphy and tectonics of the Virginia–North Carolina Blue Ridge: evolution of Late Proterozoic–Early Paleozoic hing zone. Geol Soc Am Bull 96:285–295

Williams H, Hatcher RD (1982) Suspect terranes and accretionary history of the Appalachian orogen. Geology 10:530–536

Williams H, Hatcher RD (1983) Appalachian suspect terranes. In: Hatcher RD Jr, Willians H, Zietz I (eds) Contributions to the tectonics and geophysics of mountain chains. Geol Soc Am Mem 158:33–53

Willner AP (1990) División tectonometamórfica del basamento del noroeste argentino. In: Aceñolaza FG, Miller H, Toselli A (eds) El Ciclo Pampeano en el Noroeste Argentino. Serie Correlación Geol 4:113–161

Withe R, McKenzie D (1989) Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. J Geophys Res V.94:7685–7729

Wright JE, Seiders VM (1980) Age of zircon from volcanic rocks and tectonic implications from the Carolina volcanic slate belt. Geol Soc Am Bull 91:287–294