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The proto-Andean margin of Gondwana: an introduction

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Abstract: A basic background is presented for the discussion of the Early Palaeozoic geology of western Argentina covered by this book. This includes the definition and terminology of orogenic cycles on this part of the Gondwana margin, represented by the Eastern Sierras Pampeanas. The Pampean orogeny (Early Cambrian) relates to an intense but short-lived period of terrane collision predating the rifting of the Precordillera terrane from Laurentia. The Famatinian cycle is predominantly represented by intense subduction-related magmatism of Early–Middle Ordovician age, developed on the continental margin of Gondwana during the rifting and drifting of the Precordillera terrane. The Grenvillian basement of the latter is further exemplified by a new Rb–Sr whole-rock isochron age of 1021 ± 12 Ma for orthogneisses from the Western Sierras Pampeanas. A mid-Ordovician granite in this area (dated at 481 ± 6 Ma by U–Pb ion microprobe data) may be related to rifting while the Precordillera terrane was still attached to Laurentia. A divergence of opinion is pointed out between some authors in this book who favour mid-Ordovician collision of the Precordillera with Gondwana, and others who place it much latter, in Silurian or Devonian times.

The Palaeozoic geological history of western South America has been the focus of intense international interest during the last five years. The development of this subject, and the growing state of our knowledge, can be traced from the idea of Palaeozoic continent–continent collision between North and South America along this margin (Dalla Salda *et al.* 1992*a*, *b*), through the proceedings of international conferences in Mérida, Spain ('El Paleozoico Inferior de Ibero-América', Gutierrez-Marco & Saavedra 1992), in San Juan, Argentina (Penrose Conference 'The Argentine Precordillera: a Laurentian Terrane', Dalziel *et al.* 1996), and the international symposium 'The Proto-Andean Margin of Gondwana', co-organized by IGCP projects 345 and 376 (XIII Congreso Geológico Argentino, Actas V, 257–561, Buenos Aires, 1996). A major landmark was the overall consensus reached by participants in the 1995 Penrose Conference that the Precordillera of western Argentina is an allochthonous terrane, originally detached from Laurentia (Dalziel 1997 and references therein; see also **Dickerson & Keller** this volume) and accreted to the southwestern margin of Gondwana. The timing of this transfer, and the events and processes involved in the arrival and collision of the Precordillera allochthon, have far-reaching consequences for geological, biological and palaeogeographical interpretations and the distribution of mineral resources. Many of the implications are only just beginning to be understood.

The papers presented in this book come mainly from participants in the Buenos Aires meeting in October 1996, where the latest results from various Palaeozoic provinces were discussed, including recent information on the history of the Gondwana foreland before and during the accretion of the Precordillera terrane. For a general audience, appreciation of the arguments presented requires a basic knowledge of the common geographical, geological and tectonic terminology used by South American geologists. It is the purpose of this introduction to provide an adequate background for the non-specialist. The region concerned and its relevant geographical features are illustrated in Figs 1 and 2.

The Sierras Pampeanas of western Argentina are elevated ranges of pre-Cenozoic basement rock, thought to result from uplift on reverse faults during upper Tertiary Andean deformation. This structural domain roughly coincides with a near-horizontal segment of the presently subducting Nazca plate – the 'flat-slab zone' between 27°30′ and 33°S (Isacks 1988; Jordan & Allmendinger 1986) (Fig. 1), also characterized by Miocene arc magmatism more than 700 km inboard of the Chile trench (Kay & Gordillo 1994).

The pre-Mesozoic geological record of the Sierras Pampeanas and the immediately adjacent regions is characterized by evidence of several periods of convergence along the proto-Pacific margin of Gondwana. This is the basis of the recognition of the major orogenic *cycles*, such as

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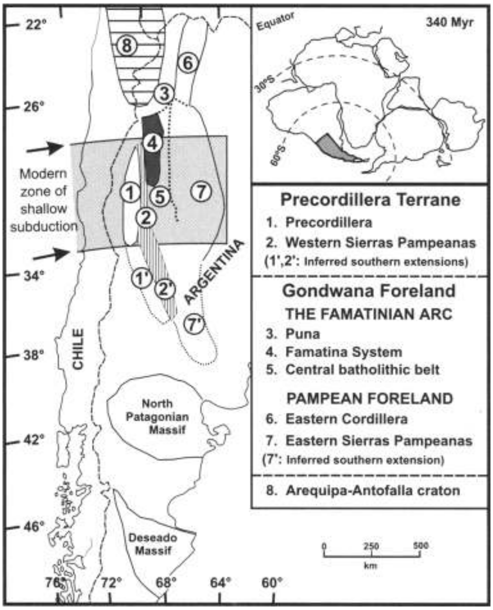


Fig. 1. Sketch map of southern South America, showing the location of the main areas of Lower Palaeozoic outcrop in western Argentina and their general nomenclature.

the *Pampean* and *Famatinian* (Aceñolaza & Toselli 1973), *Gondwanian* (Llambías *et al.* 1984) and *Andean* cycles; a brief description of the meaning that we attach to each of these terms is given in Table 1. Based on local and distinct geological characteristics, they have effectively displaced imported European and North American terms such as 'Caledonian', 'Hercynian', 'Acadian' and 'Taconic', although ironically, with a new and better understanding of continent and supercontinent configurations, the real equivalence of some of these events is now ripe for re-evaluation. Recognition, definition and ordering of the discrete phases of deformation, metamorphism and magmatism that make up these cycles requires intensive research and interpretation, and is thus sometimes a contentious subject. The chronostratigraphical limits of these large-scale geological cycles in southern South America can be ascribed to major plate re-arrangements in the evolutionary stages of the Gondwana supercontinent. The changes between these stages, and therefore in the geodynamic environment along the margin, are mostly marked by initiation, or sudden acceleration, of subduction (see Table 1). It must be stressed that the word *cycle*

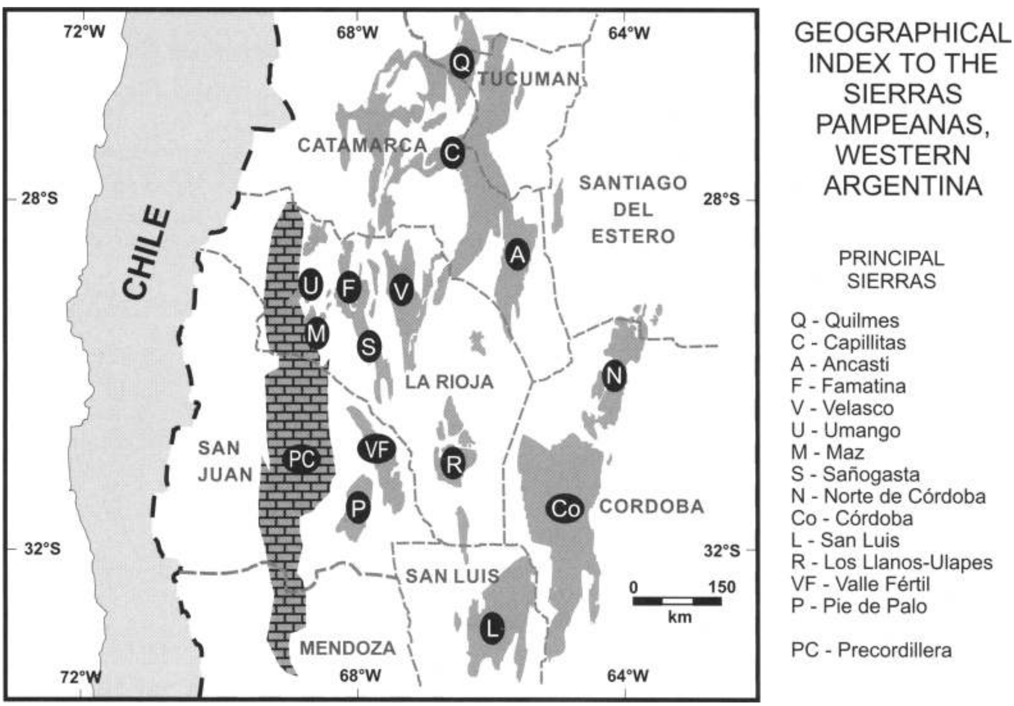


Fig. 2. Sketch map of the region of the Sierras Pampeanas and the Argentine Precordillera, the area encompassing the subject of most papers in this volume.

Table 1. *Phanerozoic geological cycles along the Pacific margin of South America*

Pampean (*Neoproterozoic–Late Cambrian*)
First recognized in the basement of the Eastern Cordillera, the Puna and the northwestern Sierras Pampeanas (Aceñolaza *et al.* 1990 and references therein), this Neoproterozoic–Cambrian cycle is now regarded as a major orogenic event in southwestern Gondwana. Along the southern proto-Andean margin, the Pampean cycle includes formation of a passive margin sedimentary basin, emplacement of metaluminous granitoid sequences, penetrative folding and low–high-grade metamorphism during mid-Cambrian time (see Rapela *et al.* this volume), and extensional collapse in the late Cambrian. The Pampean orogeny is broadly coeval with the collisional Rio Doce Orogeny, the last event of the Brasiliano–Pan African cycle along the southern coastal region of Brazil (Campos Neto & Figueiredo 1995).

Famatinian (*Early Ordovician–Early Carboniferous*)
A major accretional and orogenic episode that started with subduction along the Cambrian proto-Pacific margin (at *c.* 490 Ma). The Famatinian orogeny in the Gondwana foreland and the collision of the Precordilleran Terrane along the continental margin are usually both ascribed to this cycle, although they may not be causally related (see Pankhurst *et al.* this volume). Most of the contributions in this book are devoted to different aspects of this complex process, a summary of which is presented in Fig. 3. It should be noted, however, that mid-Palaeozoic tectonic phases registered in the clastic sequences of the Precordillera ('Precordilleran' and 'Chanic' tectonic phases, Fig. 3) have been related to the subsequent collision of another terrane ('Chilenia') to the west of the Precordillera (Ramos *et al.* 1986; Astini 1996). These tectonic events, as well as the broadly coeval intrusion of within-plate granites in the Gondwana foreland, are here tentatively included as the latest events of the Famatinian Cycle (see Fig. 3).

Gondwanian (*Early Carboniferous–Early Cretaceous*)
This was a period of the maximum extent and relative stability of the super-continent, from Lower Carboniferous (*c.* 330–340 Ma, see insert, Fig. 3) to final break-up. Following the Early and mid-Palaeozoic orogenies and accretionary events, intrusion of Carboniferous Cordilleran-type batholiths associated with a new subduction regime along the palaeo-Pacific margin heralded a major plate re-assembly. Development of extensive Permian to Jurassic rhyolitic provinces and inner cordilleran plutonic belts are characteristic of the Gondwanian cycle (Rapela *et al.* 1996).

Andean (*Early Cretaceous–Present*)
From the final break-up of Gondwana to the present. The Andean Cycle started with the opening of the South Atlantic and separation of South America from the African–Indian plate. This event was closely associated with extrusion of the Paraná–Etendeka flood basalt province (*c.* 130 Ma Renne *et al.* 1992; Turner *et al.* 1994). The generation of plutonic and volcanic rocks typical of the modern Andes became predominant as the convergence velocity at the palaeo-Pacific margin of the newly formed South American plate increased. The term 'Andean Orogeny' is linked to several compressive phases during this period, but is most commonly used for those of Tertiary and modern age. Formation of intra-continental extensional basins and a passive Atlantic margin are also typical of the Andean period.

is used here to describe stages during the *accretion* and *break-up* of a supercontinent, and not necessarily a regular or repeated succession of events. Not even the magmatic products of these subduction regimes are identical; the Famatinian, Gondwanian and Andean calc-alkaline rocks each have their own distinctive characteristics.

A summary of the major geological features and inferred tectonic events for the Precambrian and Early to mid-Palaeozoic provinces from 22 to 33°S is shown in Fig. 3, based on established literature but in some cases modified by the new results presented in this volume. The basic distinction of a *Precordillera terrane* and a *Gondwana foreland* seems useful to describe and contrast the main features of the adjacent continental masses that are inferred to have been amalgamated during the Lower Palaeozoic. The term *Precordillera terrane* is used to encompass the Lower Palaeozoic sedimentary sequences of the Precordillera, and its Grenvillian-age basement represented by the adjacent parts of the *Western Sierras Pampeanas*, as in Astini *et al.* (1995); see also **Ramos *et al.*** (this volume) who use the name 'Cuyania' for this terrane. Early Palaeozoic magmatism and metamorphism is clearly recorded in central and NW Argentina (Sierras Pampeanas, Sierra de Famatina and the Puna), extending into southern Bolivia, northeastern Chile, and the coastal areas of southwestern Peru. The main components are the Ordovician plutonic and volcanic rocks of the *Puna*, the *Famatina System*, and the *Central Batholithic Belt*, which together constitute the Famatinian magmatic arc, and the Cambrian metamorphic and plutonic igneous sequences of the *Eastern Sierras Pampeanas* and the *Eastern Cordillera* (Fig. 1). Sedimentation in the Precordillera and granitoid magmatism in

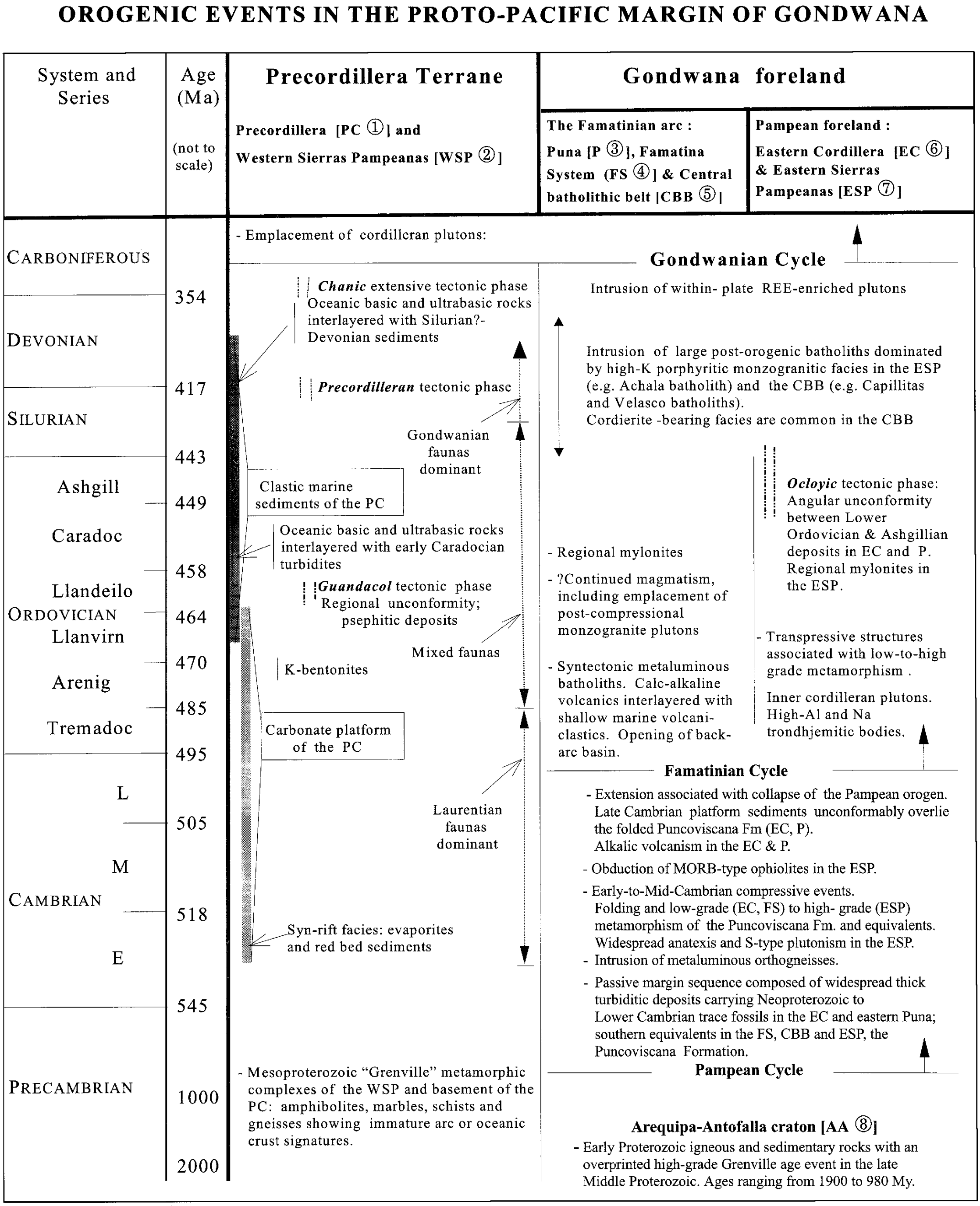


Fig. 3. Schematic representation of the main geological events recognized in the Palaeozoic history of the region, with a comparison of such event in the allochthonous Precordillera terrane and the Gondwana foreland (Eastern and Western Sierras Pampeanas).

the Eastern Sierras Pampeanas continued into Devonian–Carboniferous times, after the final assembly of this accreted margin. Carboniferous calc-alkaline magmatism to the west of the Precordillera, in Argentina and Chile, marks a yet later stage in the development of the Andean active margin that is not considered here.

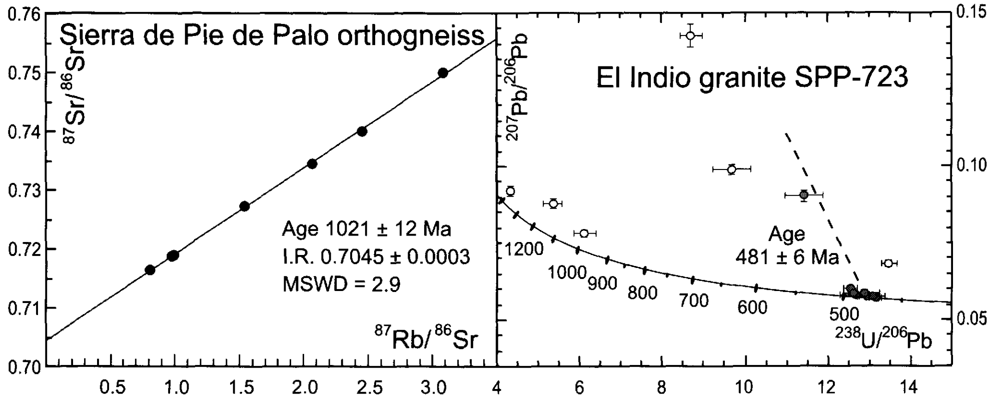
The uplifted Palaeozoic rocks of the foreland reach altitudes of over 6000 m in the Famatina System. The level of crustal exposure seems to be higher in the north, with shallow marine sediments of Lower Ordovician age and coeval volcanic and volcaniclastic sequences in the Famatina System and the Puna (**Saavedra *et al.*** this volume), and Neoproterozoic–Lower Cambrian turbiditic sediments with trace fossils in the Eastern Cordillera (see review by Bahlburg & Hervé 1997; **Bahlburg** this volume). In contrast, such supracrustal rocks are relatively rare in the southern areas, where both low- and medium-to-high grade metamorphic rocks predominate as the host rocks to Ordovician magmatism.

South of 33°S, the typical uplifted foreland block of the 'flat-slab' segment abruptly disappears. However, rocks carrying fossils typical of the carbonate platform of the Precordillera have been described at 35°S, 68°30′W in the Ponon Trehue area (Bordonaro *et al.* 1996), and poorly preserved carbonate rocks of La Pampa at 37°20′S, 67°W are also considered to be a southeasterly extension of the Precordilleran sequences (Criado Roqué 1972; Astini *et al.* 1995). Scattered outcrops of igneous and metamorphic rocks in this region have given late Proterozoic K–Ar ages (Linares *et al.* 1980), suggesting that the crystalline basement of the Western Sierras Pampeanas might also extend to these southerly latitudes (see Fig. 1 and **Ramos *et al.*** this volume). Equivalents of the Cambrian–Lower Ordovician carbonate platform of the Precordillera, the key sequences that demonstrate a Laurentian biogeographical affinity (**Benedetto** this volume and references therein), do not crop out either in Patagonia or to the north of the Precordillera; whether this is a real geological discontinuity or a coincidence of tectonic or erosion processes is still not well understood but is clearly important to the terrane accretion concept (see below).

The Precordillera Terrane

Although the basement of the Precordillera is not exposed, indirect evidence of its 'Grenvillian' characteristics and age come from U–Pb studies of xenoliths from Miocene lava domes (Kay *et al.* 1996). This has been taken as further support for the hypothesis that the Precordillera was derived from part of Laurentia corresponding to the southern Appalachians (e.g., Dalla Salda *et al.* 1992*a*; Astini *et al.* 1995). Other 'Grenvillian ages' (*c.* 1000 ± 100 Ma) have been obtained in the adjacent Sierra de Pie de Palo to the east, including U–Pb ages on orthogneiss, diorite, rhyolite and amphibolite (938 to 1091 Ma, McDonough *et al.* 1993, analytical data and errors not reported). This has lead to a growing consensus that the whole of the Western Sierras Pampeanas might represent basement remnants of an allochthonous Grenvillian terrane of which the Precordillera is only a part. Rb–Sr analysis of equivalent orthogneiss suites in the Sierra de Umango, 250 km to the north of Pie de Palo (Fig. 2), has produced a similar age of 1030 ± 30 Ma (Varela *et al.* 1996). Finally, we have ourselves obtained a new Rb–Sr whole-rock isochron of 1021 ± 12 Ma (2σ; MSWD = 2.9) for seven samples of granitic orthogneisses from the highest part of the Sierra de Pie de Palo (Fig. 4). Together with the initial $^{87}Sr/^{86}Sr$ ratio of 0.7045 ± 0.0003, this shows that the parent magmas of these gneisses were generated in Grenvillian times from an immature source. Significantly, in view of the intense Palaeozoic metamorphic and magmatic history prevalent to the east, their Rb–Sr systems show no evidence of subsequent events.

The evidence for possible Laurentian derivation of the Precambrian metamorphic sequences to the north, west, and south of the Sierras Pampeanas, is more difficult to evaluate. Small outcrops of pre-Carboniferous metamorphic rocks west of the Precordillera in both Argentina and Chile have been taken as evidence for a later exotic terrane ('Chilenia', Ramos *et al.* 1986), and some of these have now yielded Grenville-age zircon (Ramos & Basei 1997). Their reality as a separate terrane, or as part of the basement of the Precordillera terrane, is not clear, and the extent to which more distant metamorphic terranes along the proto-Andean margin can be assigned 'Laurentian' derivation is largely model dependent. For example, the Laurentian 'Occidentalia Terrane' of Dalla Salda *et al.* (1992*a*, *b*, and this volume), includes all known Precambrian outcrops along the Andean margin: the Arequipa–Antofalla craton, the Western Sierras Pampeanas and the western edge of the Patagonian massifs. A continent–continent collision between eastern Laurentia and southwestern Gondwana along the whole length of this margin is postulated in this model. However, **Dalla Salda *et al.*** (this volume) base many correlations on the original, very broad, definitions of the Pampean and Famatinian cycles (Aceñolaza &



Rb-Sr analytical data for orthogneisses and migmatites, Sierra de Pie de Palo:

Sample		Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	%s.d.	$^{87}Sr/^{86}Sr$
SPP407	Gneiss	53.2	74.7	2.0639	0.5	0.734410
SPP411	Gneiss	61.8	116.5	1.5384	0.5	0.727311
SPP412	Gneiss	44.8	131.3	0.9891	0.6	0.719007
SPP413	Granite	96.5	90.8	3.0853	0.5	0.749937
SPP414A	Gneiss	41.1	121.9	0.9755	0.7	0.718620
SPP414B	Granite	88.3	104.5	2.4525	0.5	0.740044
SPP416	Gneiss	27.9	100.4	0.8036	1.0	0.716315

Sample localities: SPP 407, Quebrada La Petaquita (31°28.02'S, 68°09.62'W), remainder around television antenna (31°18.67'S, 67°55.75'W). $^{87}Sr/^{86}Sr$ precise to ±0.01%, relative to NBS987= 0.710235

Fig. 4. New geochronological data relating to the Sierra de Pie de Palo, Western Sierras Pampeanas. (**a**) Rb–Sr isochron for orthogneisses from the central (highest) part of the sierra, indicating a Grenvillian age of formation, (**b**) U–Pb SHRIMP data for a granite emplaced into metamorphic basement in the SE part of the sierra, corresponding to an Early to Mid-Ordovician age (data available from R.J.P.).

Toselli 1973), which are at variance with the more restricted definitions shown in Fig. 3 and adopted by other authors in this volume (**Pankhurst *et al.***; **Rapela *et al.***; **Sims *et al.***). Moreover, Pb isotope studies in the Arequipa–Antofalla craton have been taken to suggest that it represents a crustal reservoir distinct from that of the Western Sierras Pampeanas and the Precordillera basement (Tosdal 1996).

Another approach is that of Astini *et al.* (1995), Thomas & Astini (1996), and **Astini** (this volume), who consider the platform of the Precordillera and its Grenvillian basement as a more restricted microcontinent (the *Precordillera Terrane* or *Cuyania*), detached from Laurentia during the Lower Cambrian and accreted to Gondwana in mid-Ordovician times after travelling independently across the Iapetus Ocean. The size of this terrane has been estimated as about 1000 km long and 400 km wide when Andean shortening is restored (Keller & Dickerson 1996), or as a block *c.* 800 km square (Thomas & Astini 1996). Dalziel (1997) proposed an alternative model in which the micro-continent that collided with Gondwana was a stretched passive margin plateau that was still connected to Laurentia during a Mid-Ordovician collision. Doubt is cast on this model by current considerations of stratigraphical and palaeontological evidence (**Astini**, this volume; **Benedetto** this volume). New ages and petrology relating the Grenville basement of the Western Sierras Pampeanas and its deformation are presented by **Ramos *et al.*** (this volume). The geochemistry and tectonic interpretation of mafic sequences in these western areas as representing a variety of Precambrian oceanic environments are considered by **Vujovich & Kay** (this volume) who identifiy some of the most primitive Precambrian magma types known.

Also shown in Fig. 4 are new U–Pb zircon data obtained by SHRIMP (ANU, Canberra) for a granite cutting the metamorphic sequence. Zircon cores show a range of inherited ages up to at least 1400 Ma, whereas data from the rims indicate an emplacement age of 481 ± 6 Ma. If this were considered part of the Famatinian cycle, it would imply that the Grenvillian basement of the Sierra de Pie de Palo had already collided with the Gondwana foreland by Early

Ordovician times. This would be consistent with the models of **Astini** and **Ramos *et al.*** (this volume), who argue for mid-Ordovician collision. However, models in which the collision of the Precordillera terrane occurred much later, in Silurian–Devonian times, are supported by some of the new evidence and interpretations presented in this volume (see **Keller *et al.***; **Benedetto**; **Pankhurst *et al.***). The palaeontological content of the Precordillera is revisited by **Benedetto**, stressing the palaeo-biogeographical links with eastern Laurentia. He suggests that the Precordillera and Gondwana faunas show differences throughout the Late Ordovician and that the first unequivocal evidence for geographical continuity between them seems to be in the Wenlockian. **Keller *et al.*** (this volume) identify major unconformities in the Precordillera succession as relating to the rifting and drifting stages of separation from Laurentia, and refute the possibility of an Ordovician collision with Gondwana. **Von Gosen & Prozzi** (this volume) consider that *post*-Famatinian compression in the Sierra de San Luis was probably synchronous with collision. The La Escalerilla granite, affected by this deformation, is of Devonian age according to Stuart-Smith *et al.* (unpublished, cited by Sims *et al.* this volume). Finally, the subduction episode that closed the Southern Iapetus Ocean, resulting in the collision of the Precordillera terrane, did not start until *c.* 490 Ma (**Pankhurst *et al.*** this volume; **Sims *et al.*** this volume) and it is therefore likely that the collision itself was much later. Our suggestion is that the mid-Ordovician granite in the Sierra de Pie de Palo is related to magmatism during the initial rifting of the terrane from Laurentia rather than to Gondwana events. Mid-Ordovician K-bentonites intercalated in the Precordillera carbonate sequences might be explained in the same way, although some authors in the present volume (**Huff *et al.***; **Dalla Salda *et al.***) prefer their previous interpretation of derivation from the Famatinian arc itself during a mid-Ordovician collisional episode.

The Gondwana foreland

Most of the geological constraints for the collision models outlined above have come from recent sedimentological and biostratigraphical studies on the Precordilleran sequences and petrological-geochronological studies of its Grenvillian basement. It is nonetheless obvious from Fig. 3 that some of these models will be severely constrained, or even discarded, when the timing, geochemical signatures and P–T–t paths of the foreland sequences and the Famatinian arc can be compared in detail with those of the inferred exotic terranes. One purpose of this book is to initiate progress towards that goal, as well as to encourage further research on the many large igneous-metamorphic areas that still lack detailed structural, petrological and isotopic studies.

Rapela *et al.* and **Sims *et al.*** discuss the Cambrian to Lower Ordovician geological characteristics of the Gondwana continental margin before the collision of the Precordillera terrane, represented by the Eastern Sierras Pampeanas and the Eastern Cordillera. Based on a new structural, metamorphic, geochemical, and geochronological study, **Rapela *et al.*** conclude that the Pampean orogeny itself resulted from a major earlier collisional event in Early to Mid-Cambrian times.

The Famatinian arc

Finally, the development of the Famatinian arc and subsequent transformation of the margin into the Gondwana foreland is treated in number of papers in this volume; in the Famatina System (**Saavedra *et al.***), the Sierra de Fiámbala (**Grissom *et al.***), the central southern Sierras Pampeanas (**Pankhurst *et al.***), and the Sierras de San Luis (**Llambías *et al.***; **von Gosen *et al.***). Further evidence for the geochronological constraints on the timing of both Pampean and Famatinian orogenic events is provided by **Sims *et al.*** These papers provide an overall picture of a calc-alkaline subduction-related magmatic arc which was active from earliest Ordovician (Tremadocian) times. In the south there is only a plutonic record and the arc was clearly developed on the margin of the Gondwana foreland that had been established during the Pampean orogeny (**Pankhurst *et al.*** this volume). Now, even in the north, the sedimentological evidence discussed by Bahlburg (this volume) appears to favour a continental arc rather than the earlier model of an island arc for the Famatinian environment at this Early Ordovician stage. Subsequently, more evolved and less deformed granitoids, some with a marked peraluminous tendency, were emplaced into the batholithic belt until mid-Ordovician times. Activity then ceased until peraluminous intra-plate magmatism restarted to the east of the old arc, in Devonian times. At this point, the Palaeozoic geological record of the Sierras Pampeanas ceased, indicating the stability of the new continental margin, at least until the start of the Andean cycle in Cretaceous times.

Interpretations presented in the contributions in this volume have in many cases developed since the 1996 congress in Buenos Aires, and we have not attempted to ensure total consistency between the various contributions. We have simply tried to point out here that radically different views are expressed concerning the duration and extent of the Famatinian arc, the question of whether this arc was an island arc or a continental one, and the timing of the final collision of the Precordillera terrane with Gondwana. The reader is invited to compare these views critically, as the resolution is necessary to reach a fully coherent understanding of the processes involved in this, one of the best-constrained allochthonous terrane histories known.

The new data referred to in this introduction were obtained as part of contract CI1-CT92-0088* from the European Commission and was also supported by grant PIP No 4148 from the Consejo Nacional de Investigaciones Científicas y Técnicas de la República Argentina (CONICET); this paper is listed as NIGL Publication No. 238. The volume as a whole is a contribution to IGCP Projects 345 (Andean Lithospheric Evolution) and 376 (Laurentia–Gondwana Connections before Pangea).

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