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New isotopic dating of intrusive rocks in the Sierra de San Luis (Argentina): implications for the geodynamic history of the Eastern Sierras Pampeanas

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Abstract

U–Pb datings of zircons from intrusions in the metamorphic complex of the Sierra de San Luis (Eastern Sierras Pampeanas, Argentina) suggest that the depositional, tectonic, metamorphic, and magmatic history in this part of the Pampean Terrane spans the Proterozoic through Early Paleozoic time interval. The Paso del Rey Granite intruded a clastic succession at 608 + 26/−25 Ma and, afterward, was deformed together with the country rocks. The intrusions of the Río Claro Granite and La Escalerilla Granite at 490 ± 15 and 507 ± 24 Ma, respectively, mark the onset of Famatinian arc plutonism due to east-directed subduction beneath the Eastern Sierras Pampeanas. The new data, along with structural analyses and published results of isotopic dating, allow an interpretation of the history in this segment of the Pampean Terrane. After basement formation, Late Proterozoic turbiditic sedimentation in a passive margin setting was accompanied by block faulting and continued at least to the Early Cambrian. It is assumed that the Pampean Terrane represents a detached fragment of the Río de La Plata Craton in the east. The first deformation in the Micaschist Group was an effect of an early stage of the compressive Pampean event, which is related to the collision of the Pampean Terrane with the Río de La Plata Craton. The Early Cambrian is recorded by injections of acid magmatic sills and dykes, probably under overall crustal extension. This also indicates an age of the turbiditic sediments comparable to that of the Puncoviscana Formation s.l. of northwest Argentina. After cessation of Famatinian arc plutonism, compression and regional metamorphism affected the intrusives, clastic succession, and older basement units. The related amalgamation of the Cuyania (Precordillera) Terrane with the Eastern Sierras Pampeanas was completed during the Early Devonian.

Keywords: U–Pb datings; Metamorphic complexes; Intrusions; Sierras Pampeanas

1. Geological situation

In western Argentina, the Sierra (Grande) de San Luis lies at the southern tip of the Eastern Sierras Pampeanas Complex, which is interpreted as a Late Proterozoic–Earliest Paleozoic terrane ('Pampean Terrane'; cf. Ramos, 1988) accreted to the Río de La Plata Craton in the east during Early to Mid-Cambrian times (e.g. Rapela et al., 1998a,c). Just to the west of the Sierra follows the inferred suture with the Laurentia-derived Cuyania (Precordillera) Terrane (Fig. 1; compare, e.g. Schmidt et al., 1995; Ramos et al., 1996; von Gosen and Prozzi, 1998) or 'Texas Plateau' (Dalziel, 1997). Thus, the tectonic, magmatic, and metamorphic evolution in the Sierra de San Luis can provide evidence for the evolution of the Pampean Terrane and an insight into the timing of the docking of the Cuyania (Precordillera) Terrane, which is still a matter of debate (Ordovician versus Silurian/Devonian; e.g. Astini et al., 1995; Ramos et al., 1996, 1998; Dalziel, 1997; Astini, 1998; von Gosen and Prozzi, 1998; Keller et al., 1998; Keller, 1999; Rapela et al., 1998b,c, 1999).

The mountain chain of the Sierra de San Luis consists of metamorphic and (meta-)magmatic rocks (for recent overviews, see von Gosen and Prozzi, 1998; Llambías et al., 1998; Sims et al., 1998). The long-lasting magmatic, deformational, and metamorphic history was terminated prior to the deposition of Late Carboniferous–Early Permian clastic sediments. The present half-horst structure of the sierra is the result of Late Tertiary–Quaternary (Andean) compression.

The metamorphic complex is built up of several contrasting units (Fig. 2). In the western and central part, the

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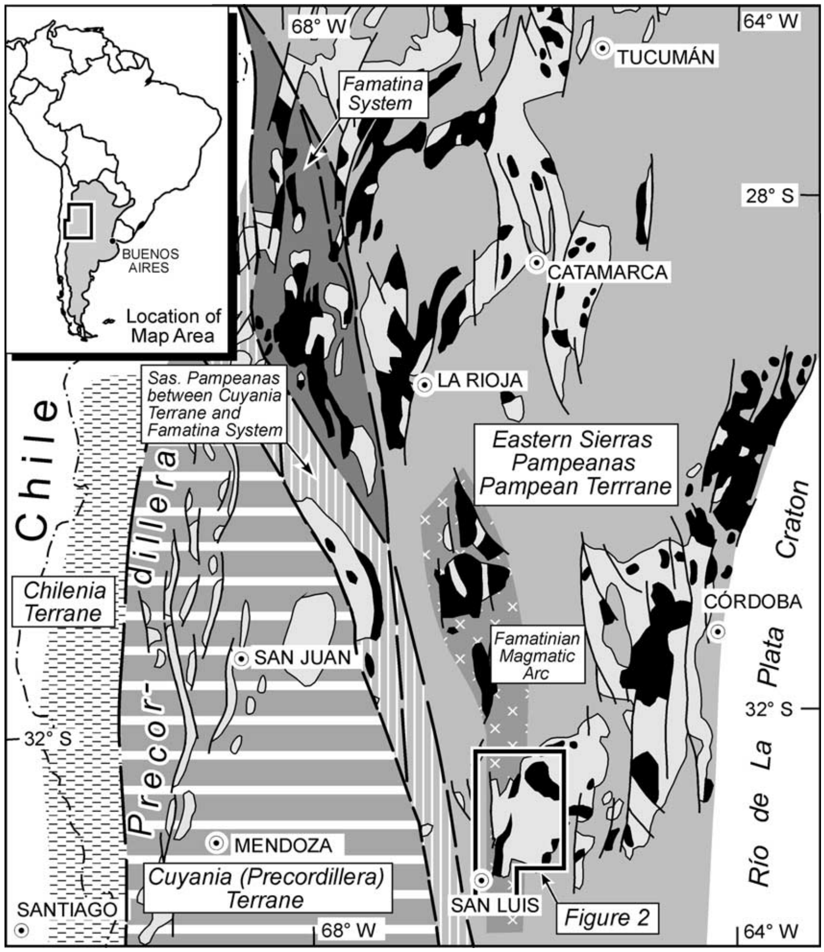

Fig. 1. Simplified sketch map of the main geotectonic units in western Argentina (modified from von Gosen (1998b)). Boundary between Pampean Terrane and Río de La Plata Craton is inferred; granitoids are indicated in black. Frame depicts location of map of Fig. 2. Geotectonic units: light grey—area of the Eastern Sierras Pampeanas (Pampean Terrane); dark grey—Famatina System; vertically ruled—Sierras Pampeanas between Famatina System and Cuyania (Precordillera) Terrane; horizontally ruled—Cuyania (Precordillera) Terrane; and dashed—Chilenia Terrane.

Western and Eastern Basement Complexes consist of gneisses, quartzites, injected micaschists, migmatites, and intercalated amphibolites. Lens-shaped mafic/ultramafic complexes occur in the Eastern Basement Complex. The age of the basement units has been assigned as Cambrian and Cambro-Ordovician (Sims et al., 1998; their 'Nogolí' and 'Pringles Metamorphic Complexes') or partly as Proterozoic (e.g. von Gosen and Prozzi, 1998). The Phyllite Group ('San Luis Formation' of Prozzi and Ramos (1988)) forms two strips, which indicates the general NNE–SSW structural trend in the metamorphic complex. This unit has been compared with the Puncoviscana Formation s.l. of northwest Argentina (Prozzi and Ramos, 1988; Prozzi, 1990). Strips of the Micaschist Group are parallel to the phyllites or the long lamellae of the La Escalerilla Granite in the southwestern part of the Sierra (Fig. 2). The Micaschist Group has been interpreted as a higher metamorphic equivalent of the Phyllite Group (von Gosen, 1998a,b).

Various granitoids in the metamorphic complex are related to pre-, syn-, and post-kinematic stages of intrusive activity (Llambías et al., 1991, 1996a; Sato and Llambías, 1994; Varela et al., 1994). Pre-kinematic plutons are mostly tonalites, granodiorites, and granites in the western part of the Sierra (see, for example, Ortíz Suárez et al., 1992; Sato, 1993; Brogioni et al., 1994; Sato et al., 1996, 1999). On the basis of geochemical characteristics, isotopic data, and structural analyses, they are interpreted as part of an Early to Mid-Ordovician (Famatinian) magmatic arc (e.g. Sato et al., 1996; Llambías et al., 1998; Sims et al., 1998; von Gosen and Prozzi, 1998), with a possible onset of intrusive activity in the Cambrian (Sato et al., 1999). The continental arc extends farther northward in the Sierras de Chepes, Ulapes, and Las Minas, where plutonism spans the Early to Middle Ordovician interval (cf. Rapela et al., 1998b, 1999; Pankhurst et al., 1998). The term 'Famatinian Cycle' has been proposed by Aceñolaza and Toselli (1976) to span the Late Cambrian to Devonian period, though the precise time span and significance of different tectonic and magmatic events are matters of debate (compare e.g. Pankhurst and Rapela, 1998).

Syn-kinematic granites to granodiorites in the Sierra de San Luis are interpreted as of Ordovician age (Ortíz Suárez

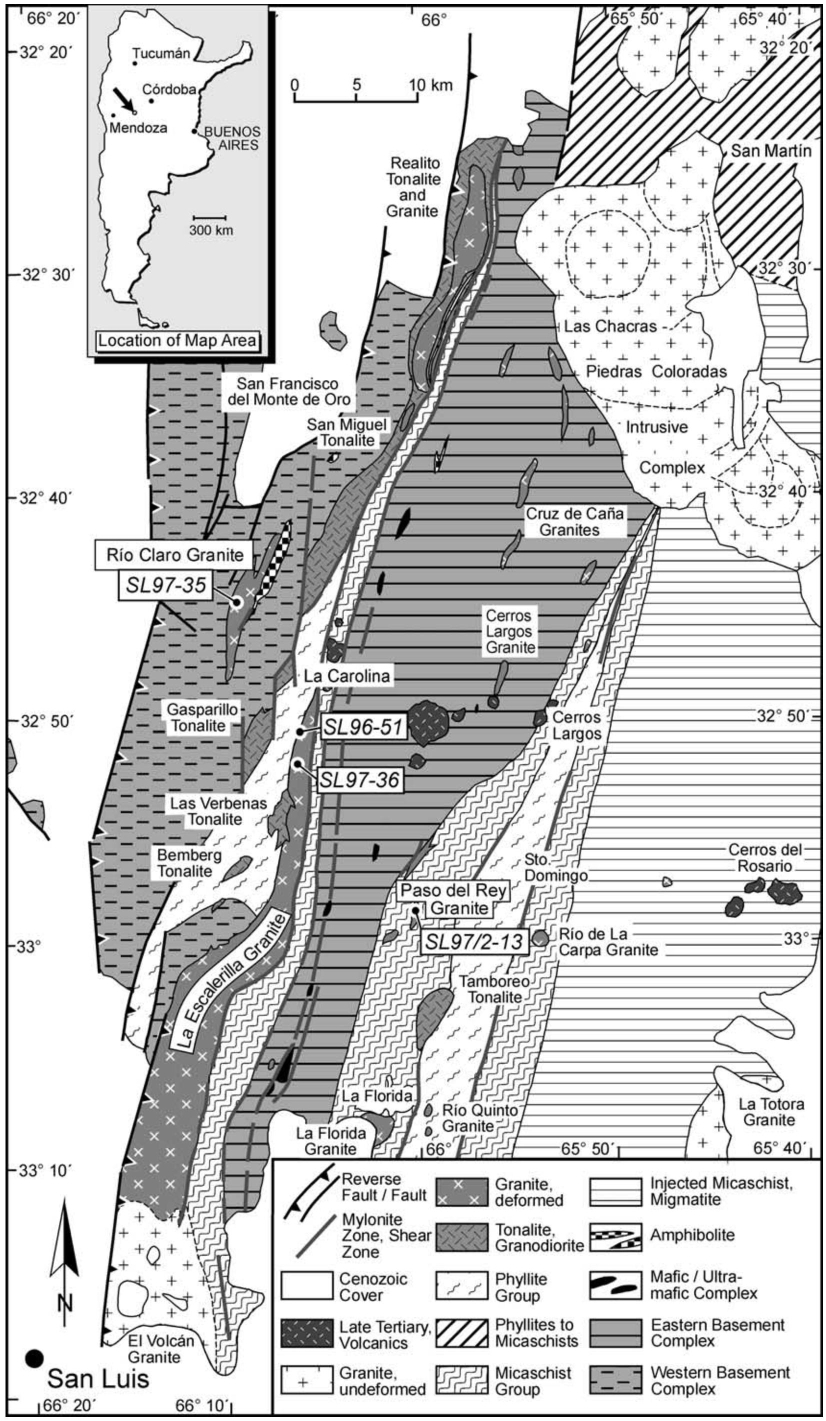

Fig. 2. Geological sketch map of the western and central part of the Sierra de San Luis with sample locations. For location of map, compare Fig. 1.

et al., 1992; Llambías et al., 1991, 1996a, 1998). Llambías et al. (1998) have shown that the Paso del Rey Granite is part of a group of anatectic garnet-muscovite granodiorites and granites with high initial $^{87}Sr/^{86}Sr$ ratios and S-type compositions. They favor the model of magma genesis in a thickened crust, supported also by high La/Yb ratios. Along with the Paso del Rey Granite, the Cruz de Caña, Cerros Largos, and Río de La Carpa plutons in the western part of the Sierra are thought to be part of this group.

The final stage of magmatic activity is indicated by large post-kinematic plutons, which span the Devonian to Early Carboniferous interval and are partly fracture-controlled intrusions (compare, e.g. Brogioni, 1987, 1992, 1993; López de Luchi, 1993; Llambías et al., 1998).

In this text, we report new U–Pb datings of zircons from three intrusions in the western and central part of the Sierra de San Luis. As the plutons intruded different country rocks, these isotopic markers, combined with published results of dating and structural analyses, will lead us to an interpretation of the structural and metamorphic evolution of the metamorphic complex. It extends and partly modifies the analysis by von Gosen and Prozzi (1998), as well as provides a picture of the Precambrian through Early Paleozoic evolution of the Pampean Terrane in this segment of the western, pre-Andean Gondwana margin.

2. Sample locations

In the metamorphic complex of the Sierra de San Luis, the Paso del Rey Granite (leuco-granodiorite; Varela et al., 1994) consists of two elongated smaller bodies within the Micaschist Group (Fig. 2). The southern occurrence of the granite has been sampled in its central, less deformed part (SL97/2-13). The sample location is 4.5 km to the south of the small village of Paso del Rey, east of the road to Pampa del Tamboreo and La Florida. There, the coarse-grained granite contains biotite and muscovite, a weak foliation, and is cross-cut by single, dm-thick shear zones. This part of the intrusion is in contrast with its foliated margins, along with long apophyses in the surrounding micaschists.

The Río Claro Granite is a north–south-trending body within the Western Basement Complex of the sierra. It truncates the multiply deformed and metamorphosed basement rocks, and both together are heterogeneously sheared. The sample location (SL97-35) is to the northwest of the village of La Carolina at the road to San Francisco del Monte de Oro, 2.3 km west of Río Claro. There, a coarse-grained, more porphyric, and foliated part of the granite is exposed.

At a length of more than 50 km, the La Escalerilla Granite (monzogranite to granodiorite; Llambías et al., 1998) extends through the southwestern part of the Sierra de San Luis. Its eastern margin is marked by a mylonite zone, along which the western strip of the Micaschist Group was obliquely reverse faulted over the granite (von Gosen and Prozzi, 1996, 1998; von Gosen, 1998b). At the western edge, the granite intruded Phyllite Group rocks in the northern segment and, in the central segment, the Western Basement Complex (Fig. 2).

For sample collection, fresh road cuttings 5.6 km south of La Carolina at the asphalt road to El Trapiche (SL96-51) and an outcrop 250 m east of the Estancia El Pílar, 8.5 km south of La Carolina and east of the asphalt road (SL97-36), were chosen. In the first outcrop, marginal parts of the biotite granite are penetratively foliated. In the second occurrence, the coarse-grained and more porphyric, slightly foliated granite represents the more central part of the pluton. A description of the sample preparations and analytical procedures is given in Appendix A.

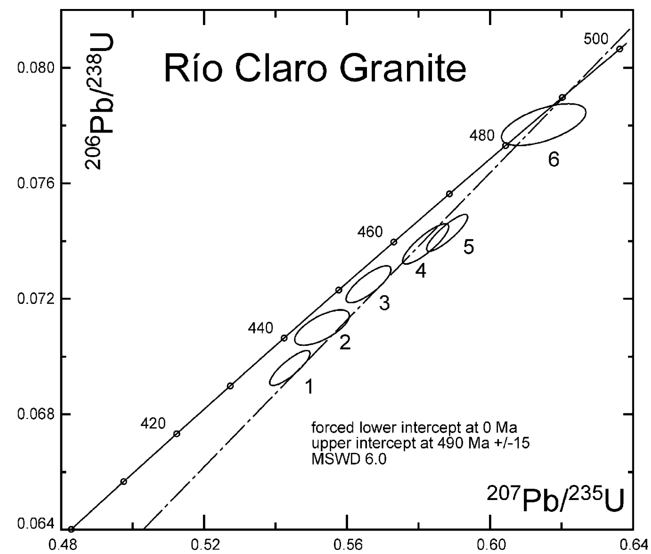

Fig. 3. Concordia diagram of single zircons from the Río Claro Granite (SL97-35).

3. Description of the zircons, their genetic interpretation, and age

3.1. Río Claro Granite

The Río Claro Granite is dominated by two types of zircons. Both types are colorless and clear. Opaque inclusions are scarce, whereas colorless crystal-shaped (apatite?) are common. Type 1 zircons are very longprismatic, with ratios of 5:1–7:1, which show the Pupin characteristics of J5, S25, D, and P5 zircons (Pupin, 1988). The Type 2 zircons are mid- to shortprismatic (2:1–3:1). They are similar to the S5, S10, P1, and P2 types. Following the Pupin classification scheme, the zircons could represent the trends 5 or 6, which are both characteristic of mantle-induced or mantle-influenced granitoids. The very high U contents of some grains (up to 5000 ppm) is in concordance with an alkaline granitoid provenance, which are generally rich in U and Th (Pupin, 1992, 1994). Following Pupin (1988), these very elongate, Type 1 zircons formed in an early hypersolvus-alkaline phase of the magma evolution.

The U–Pb system of the six analyzed zircon grains (Fig. 3) is slightly discordant with respect to the concordant low U zircon, within error limits (No. 6; 902 ppm U; $^{207}Pb/^{235}U$ apparent age = 484 Ma; see Table 1). The other zircons with higher U contents are more discordant, which is an effect of U decay that weakened the crystal lattice for Pb diffusion.

Field observation and the results of the U–Pb analysis of the zircons from the surrounding granites support the assumption of a single, very recent Pb loss event for the entire sampled area. Therefore, a calculated regression line with a fixed lower intercept at 0 ± 5 Ma leads to a calculated upper intercept at 490 ± 15 Ma (95% confidence level).

Table 1
Analytical data

Río Claro Granite, SL97-35, Muenster

Sample number	1	2	3	4	5	6
U (ppm)	4326	1508	1779	4942	4092	902
Pb (ppm)	303	110	128	367	304	73
206/204	1132.3	413.6	869.2	1448.4	1489.6	296.3
207*/206*	0.05665	0.05651	0.05661	0.05709	0.05738	0.05719
Err (1sigma abs.)	0.00013	0.00024	0.00015	0.00014	0.00011	0.00037
207*/235 ratio	0.5436	0.5535	0.5657	0.5816	0.5877	0.6153
Err (1sigma abs.)	0.0023	0.0031	0.0026	0.0026	0.0023	0.0048
206*/238 ratio	0.06959	0.07103	0.07247	0.07388	0.07428	0.07803
Err (1sigma abs.)	0.00025	0.00025	0.00026	0.00028	0.00026	0.00030
206*/238 age (Ma)	433.7	442.4	451.0	459.5	461.9	484.4
207*/235 age (Ma)	440.8	447.3	455.2	465.5	469.4	486.9
207*/206* age (Ma)	478.0	472.6	476.5	495.1	506.2	498.9
Rho (6/8–7/5)	0.84	0.68	0.80	0.85	0.87	0.59

Paso del Rey Granite, SL97/2-13, Muenster

Sample number	1	2	3	4	5	6
U (ppm)	754	838	982	1075	965	1104
Pb (ppm)	28	38	46	64	68	91
206/204	115.7	78.2	144.2	125.3	160.1	296.7
207*/206*	0.05956	0.06023	0.06052	0.05988	0.05910	0.06031
Err (1sigma abs.)	0.0014	0.0012	0.0007	0.0008	0.0006	0.0003
207*/235 ratio	0.2698	0.2749	0.3442	0.4075	0.5039	0.6490
Err (1sigma abs.)	0.0068	0.0064	0.0053	0.0065	0.0061	0.0045
206*/238 ratio	0.03285	0.03311	0.04125	0.04936	0.06183	0.07804
Err (1sigma abs.)	0.00016	0.00019	0.00034	0.00022	0.00038	0.00032
206*/238 age (Ma)	208.4	210.0	260.6	310.6	386.8	484.4
207*/235 age (Ma)	242.5	246.6	300.4	347.1	414.3	507.8
207*/206* age (Ma)	587.6	611.7	622.2	599.2	570.8	614.8
rho (6/8–7/5)	0.54	0.59	0.64	0.54	0.62	0.66

La Escalerilla Granite, SL97-36, Muenster

Sample number	1	2	3	4
U (ppm)	4139	4039	3008	2498
Pb (ppm)	111	158	151	132
206/204	165.1	169.2	264.6	319.0
207*/206*	0.05840	0.05695	0.05786	0.05672
Err (1sigma abs.)	0.00057	0.00058	0.00089	0.00055
207*/235 ratio	0.1862	0.2635	0.3685	0.3889
Err (1sigma abs.)	0.0022	0.0032	0.0061	0.0043
206*/238 ratio	0.02313	0.03356	0.04619	0.04972
Err (1sigma abs.)	0.00011	0.00016	0.00023	0.00019
206*/238 age (Ma)	147.4	212.8	291.1	312.8
207*/235 age (Ma)	173.4	237.5	318.5	333.6
207*/206* age (Ma)	544.6	489.8	524.6	480.8
Rho (6/8-7/5)	0.57	0.56	0.40	0.50

Zircon fractions, SL96-51, Munich

Sample number	5 (125–100)	6 (100–80)	7 (63–40)	8 (80–63)	9 (63–40)
Weight (g)	0.0003	0.000332	0.000569	0.000742	0.00039
U (ppm)	909	846	972	922	964
Com. Pb (ppm)	4.6	3.1	3.3	3.1	4.4
[206] (nmoles/g)	178	180	215	199	229
206/204	578	859	981	950	765
206*/238	0.04558	0.04986	0.05220	0.05079	0.05560
Err (2sigma%)	0.09	0.09	0.15	0.12	0.19
207*/235	0.3531	0.3978	0.4070	0.4081	0.4478
Err (2sigma%)	0.55	0.49	0.25	0.16	0.22
207*/206*	0.05618	0.05787	0.05655	0.05827	0.05841
Err (2sigma%)	0.51	0.46	0.19	0.1	0.11
206*/238 age (Ma)	287.3	313.7	328.0	319.4	348.8
207*/235 age (Ma)	307.0	340.1	346.7	347.5	375.8
207*/206* age (Ma)	459.6	524.9	473.9	540.0	545.2
[U] (2sigma%)	0.12	0.12	0.17	0.15	0.20
rho (6/8–7/5)	0.53	0.51	0.64	0.80	0.86

3.2. La Escalerilla Granite

The La Escalerilla Granite has been sampled at two different localities. The zircons from SL96-51 are colorless to delicate red with very glossy and excellent developed crystal faces. Opaque and colorless crystal-shaped inclusions are frequent. Mid- to longprismatic zircon crystals from the La Escalerilla Granite are similar to the S14, S5, S10, and S9 types of the Pupin classification; very large crystals tend to have S5–S4 Pupin shapes, and the amount of turbid crystals is increased. The $^{206}Pb/^{238}U$ apparent ages of the zircon fractions scatter around 287–349 Ma, and the U concentration is approximately 900 ppm (see Table 1).

Sample SL97-36 is composed of two different zircon populations. Type 1 is colorless and euhedral with frequent colorless bubbly inclusions and clear, crystal-shaped inclusions. The Pupin characteristics are dominated by S9, S10, S14, and S15 types. Type 2 is euhedral, slightly reddish, and mainly shortprismatic. Opaque inclusions are very frequent, and many crystals show growth hindrances or irregular, corrosive figures. The crystal faces show a mother-of-pearl-like luster. Many crystals are turbid, probably due to their high U contents of 2500–4000 ppm. Mainly mid- to longprismatic crystals show the characteristics of P1, P2 and S5, S10 zircons. The $^{206}Pb/^{238}U$ apparent ages of the analyzed individual zircons scatter around 147 and 312 Ma.

The Pupin characteristics of the zircons are typical for metaluminous, calcalkaline orogenic granitoids, in that the Type 1 zircons mark the beginning of the evolutionary trend of the hybrid magma and the Type 2 zircons the highly evolved stage. The characteristic U contents of the zircons from samples SL96-51 and SL97-36 express the two different facies of the La Escalerilla Granite; the higher U contents of the latter indicate a more central position of the intrusion.

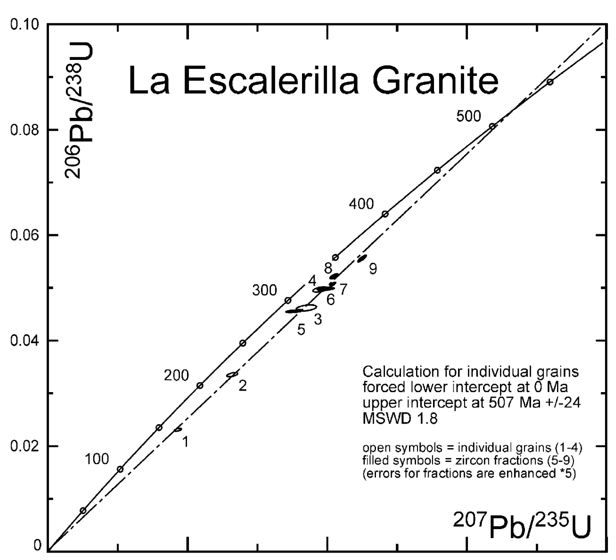

Fig. 4. Concordia diagram of the La Escalerilla Granite based on single zircons from SL97-36 and zircon fractions from SL96-51.

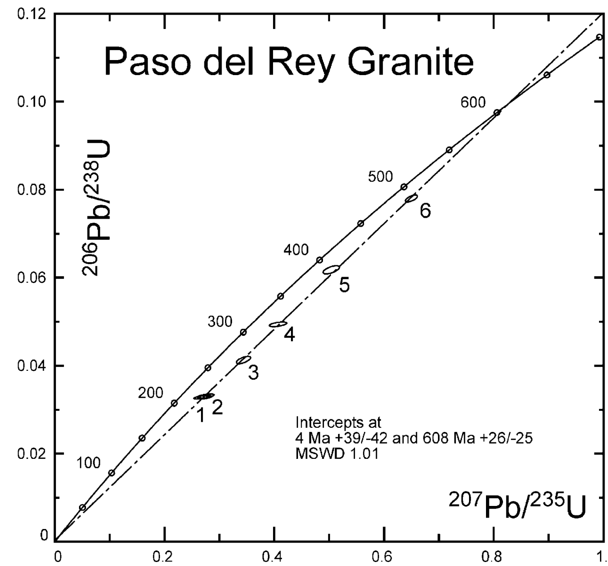

Fig. 5. Concordia diagram of single zircons from the Paso del Rey Granite (SL97/2-13).

The analyzed zircon fractions of sample SL96-51 (filled symbols) and the single-grain analyses of sample SL97-36 (open symbols) are highly discordant and, in a Concordia diagram, plot on a line that roughly intersects the Concordia at approximately 500 Ma (Fig. 4). A calculated discordia for the single-grain analyses intersects the Concordia at 507 ± 24 Ma (95% confidence level; MSWD 1.8), if the lower intercept is forced through the origin. The 'mathematical' concentration of the Pb loss of the zircons in a single, recent event is supported by the field observation that the main deformation/shearing of the granite is restricted to discrete zones, whereas the main coarse-grained body (sample SL97-36) is only characterized by a weak foliation.

The data from the analyzed zircon fractions of the sample from the marginal region of the granite (SL96-51) scatter around the regression line defined by the single-grain analyses, but the high discordance and the small spread does not allow for a calculation of a meaningful discordia. At least and aside from field observation, the data argue for a single granite body.

3.3. Paso del Rey Granite

The Paso del Rey Granite contains colorless and slightly reddish euhedral zircons. The reddish color is an effect of red-colored (haematitic?) overgrowth. Inclusions are rather scarce, and most of the crystal faces show a vitrious luster, but the iridescent luster of some individuals and deep cavities display corrosive phases in their growth history. The mainly mid- to shortprismatic zircons show the equilibrium tracht – Pupin characteristics of the S13–S14 types. Very large crystals are similar to the L5–P1 types, which formed at the end of the magma evolution. This is not in contrast with the idea of a peraluminous, collision-related crustal origin of the granitoid, which is supported by the rather high garnet contents of the granitoid.

The U–Pb system of the six individual grains is discordant from 20 to 70%. Zircons with higher U contents (1100 ppm) are less discordant than are low U zircons (800 ppm). This large spread permits a discordia calculation with an MSWD of 1.02, which intersects the Concordia at 4 + 39/−42 and 608 + 26/−25 Ma (Fig. 5; 95% confidence level). The (unforced) recent calculated lower discordia intercept of the oldest granite body of the studied area clearly shows that, between intrusion and very recent Pb loss, there has been no major event that significantly opened the U–Pb system of the zircons.

4. Discussion

In the concordia diagram, the good alignment of points suggest an age of the Paso del Rey Granite of 608 + 26/−25 Ma. This datum is greater than expected and in contradiction with previous age interpretations (Llambías et al., 1991, 1996a; Ortíz Suárez et al., 1992). The good isochron fit in the diagram, however, shows that an Ordovician age can be excluded. It further suggests that the zircons crystallized in the magma and do not represent inherited zircons from the country rocks (micaschists). Hence, we interpret the datum as indicating a Precambrian age of the intrusion.

The granite formed in an early crustal anatexis event (see also Llambías et al. (1998)), probably either during continent–continent collision or through heating of the weakened thick continental crust. A hybrid character, due to batch heat transfer by mantle material, is evidenced by the presence of the P1–S5 zircons. These are the relicts of a highly evolved, mantle-induced component.

The intrusion of the hybrid La Escalerilla Granite probably took place during the magmatic underplating of the magmatic arc. Although affected with a large error, we interpret the 507 ± 24 Ma date as an indicator of an early Famatinian emplacement of the pluton.

Sims et al. (1998) proposed an Early Devonian age of intrusion based on SHRIMP data from single zircons (403 ± 6 Ma). Their sample location lies in the southern part of the mapped granite body. According to our field observations, this porphyric granite intruded the deformed La Escalerilla Granite and equivalents, as well as intensely foliated micaschists. Therefore, we think it represents a younger granite ('El Volcán Granite'), which could be part of the post-tectonic granites in the Sierra de San Luis. This explains the contradiction between the Early Devonian age reported by Sims et al. (1998) and our 507 ± 24 Ma datum found for the northern part of the granite body.

The 507 ± 24 Ma date shows that the northern and central parts of the La Escalerilla Granite are at least Early Ordovician in age. It is reasonable to suggest that the granite belongs to the Early Famatinian suite of tonalites, granodiorites, and granites as part of the magmatic arc in the western part of the Sierra de San Luis.

The alkaline Río Claro Granite intruded during a crustal relaxation/extension process. The date of 490 ± 15 Ma is in good agreement with that for the La Escalerilla Granite and clearly shows that this granite intruded during the early stage of Famatinian igneous activity.

5. Timing of sedimentation, magmatism, and deformation in the Sierra de San Luis

The high age of the Paso del Rey Granite sheds doubt on previous interpretations regarding the age and emplacement of this intrusion and, furthermore, the timing of deformational and metamorphic events in the Sierra de San Luis and surroundings. According to the field relationships with the country rocks, the granite intruded the undeformed clastic succession of the later micaschists and led to a widely distributed growth of porphyroblasts (von Gosen, 1998a). The present age of 608 + 26/−25 Ma shows that the intruded clastic succession must be of Precambrian age. It has been compared to the Phyllite Group of the Sierra and with the Puncoviscana Formation s.l. of northwest Argentina (von Gosen, 1998a). It is noteworthy that recent K–Ar dating of the Puncoviscana Formation s.l. has also given dates greater than 600 Ma (Do Campo et al., 1999), suggesting a thermal event in Neoproterozoic times.

The northern body of the Paso del Rey Granite, along with related pegmatites, intruded the contact between the Micaschist Group and Eastern Basement Complex (von Gosen, 1998a; von Gosen and Prozzi, 1998), which consists of migmatites, gneisses, injected micaschists, amphibolites, and mafic/ultramafic complexes. Assuming an age comparable to that of the southern body, faulting with relative displacement of both units took place before but still during Late Proterozoic times. Hence, great amounts of deformation and high-grade metamorphism in the Eastern Basement Complex to the west could be Proterozoic in age.

It should be noted that small granite bodies intruded this deformed and metamorphosed basement complex (e.g. Cruz de Caña, Cerros Largos). In the Cerros Largos area, cooling of the granite interferes with final folding of the country rocks (injected micaschists and migmatites). The Cruz de Caña Granites have been affected only by later local shearing at the margins. Assuming an Ordovician age for these plutons, the country rocks, as well as their major structures, are pre-Famatinian in age. However, if the genesis of the plutons is related to that of the Paso del Rey Granite, as was shown by Llambías et al. (1998), a Proterozoic age of this basement is realistic.

The ages of the Western Basement Complex and Phyllite Group are indicated by observations and data as follows:

(1) The Río Claro Granite, La Escalerilla Granite, and Gasparillo Tonalite intruded the multiply deformed and metamorphosed Western Basement Complex, indicating the pre-Famatinian age of its deformational and metamorphic events, as proposed by Llambías et al. (1996b).

This is supported by the U–Pb dates presented here. They show that both granites represent Early Famatinian intrusions and are part of the magmatic arc that continues northward in the Sierras de Las Minas, Chepes, and Ulapes (compare, e.g. Pankhurst et al., 1998).

(2) The La Escalerilla Granite, Gasparillo, and Las Verbenas Tonalites also intruded the undeformed rocks of the Phyllite Group. The Bemberg Tonalite, dated at 512 ± 16 Ma (Rb–Sr, whole rock; Sato et al., 1999) and 468 ± 6 Ma (U–Pb, zircons, SHRIMP; Sims et al., 1998), intruded these clastic sediments, plus intercalated acid magmatic dykes and sills (von Gosen, 1998b). This shows that the protoliths of the phyllites are pre-Ordovician in age and comparable with the Puncoviscana Formation s.l. They are in clear contrast with the Western Basement Complex with its polyphase deformation and metamorphism.

(3) The rocks of the Phyllite Group to the east of the Western Basement Complex are cross-cut by acid metamagmatic layers, representing dykes and sills in the area of Pancanta (von Gosen, 1998b). U–Pb age determinations of zircons from two layers have given an Early Cambrian age (529 ± 12 Ma; Söllner et al., 2000), which has been interpreted as representing the age of zircon growth in the magmatics. This suggests that the main Pampean event in the Sierra de San Luis had its only expression in the generation of such magmatic rocks and did not lead to compressive deformation and metamorphism (e.g. in the basement complexes). All this shows that the protoliths of the Phyllite Group have an age comparable to that of the Puncoviscana Formation s.l., as proposed by Prozzi and Ramos (1988) and Prozzi (1990) and therefore can be compared to the protoliths of the Micaschist Group in the Sierra de San Luis (von Gosen, 1998a).

Structures of a single deformational event in the micaschists of the northwestern part of the Sierra de San Luis are intruded by the San Miguel tonalite. First deformational structures in the micaschists in the south and southeast affect the Paso del Rey Granite but not the La Escalerilla Granite. Therefore, these structures can be interpreted as the effect of localized ductile shearing in the lower part of the sedimentary pile and related to Latest Proterozoic–Earliest Cambrian onset of deformation in the Pampean collisional belt in the east.

(4) As the Gasparillo Tonalite intruded both the multiply deformed and metamorphosed Western Basement Complex and the undeformed rocks of the (later) Phyllite Group to the east (von Gosen and Prozzi, 1996, 1998), the basement must have been juxtaposed against the clastic succession prior to Early Famatinian pluton emplacement. This is obvious also at the eastern boundary of the Western Basement Complex to the north, which is widely injected by tonalites to granodiorites (Fig. 2). Hence, it is reasonable to assume that the Western Basement Complex of the Sierra de San Luis is Proterozoic in age, which also applies to its polyphase deformation and metamorphism (von Gosen and Prozzi, 1998).

Based on the long extent of the La Escalerilla Granite being in intrusive contact with different units in the western part of the Sierra (Fig. 2), its emplacement probably followed an old fault line, which should be pre-Ordovician in age. The granite also intruded the Las Verbenas tonalite (Sato, 1993; von Gosen, 1998b) at 507 ± 24 Ma. Furthermore, the Tamboreo Tonalite, dated at 470 ± 5 Ma (U–Pb, zircons, SHRIMP; Sims et al., 1998), intruded the boundary between the phyllites and micaschists (Fig. 2). In addition, the contact between the Eastern Basement Complex and Micaschist Group in the east is widely obscured by small granitoid intrusives.

The Phyllite Group plus intercalated dykes and sills, Micaschist Group, and La Escalerilla Granite were deformed and metamorphosed together with the arc tonalites in the west, indicating a dominant event after arc magmatism had ceased. Deformation under greenschist facies metamorphic conditions represents the first event recorded in the Phyllite Group, whereas the Western and Eastern Basement Complexes have been overprinted by heterogeneous shear zone deformation (e.g. von Gosen and Prozzi, 1996, 1998; von Gosen, 1998b).

The precise age of this Famatinian tectonic and metamorphic overprint is not recorded in the U–Pb system of the La Escalerilla Granite zircons. A Rb–Sr date of the La Escalerilla Granite at 414 ± 12 Ma has been reported by Sato et al. (1999) and interpreted as an Early Devonian age of emplacement directly followed by deformation and metamorphism. According to the datum presented here, the Rb–Sr date reflects only the age of deformation and metamorphism. This is supported by Ar–Ar data on phyllosilicates from various shear zones (Sims et al., 1998), as well as K–Ar data from biotites of intrusions (Linares and Latorre, 1973; Varela et al., 1994), which span the ~350– ~ 390 Ma interval. Because many parts of the meta-clastic successions, however, are affected by static metamorphic conditions after cessation of deformation, these dates indicate the final decrease in temperature and, thus, the closure of the various isotopic systems.

6. Interpretation of the evolution in this segment of the western Gondwana margin

During Proterozoic times, the Western Basement Complex of the Sierra de San Luis has been formed. At least three stages of deformation under a medium- to high-grade metamorphism could be detected (González and Llambías, 1998; von Gosen and Prozzi, 1998). It is possible that the Eastern Basement Complex also was affected by deformation and metamorphism during Precambrian times. The precise timing of basement formation is unclear. Rapela et al. (1998a) report that the major rock-forming event in the deep crust of the Sierras de Córdoba was Paleo- or Mesoproterozoic in age, based on Nd model ages and zircon inheritance. This is supported by Nd model

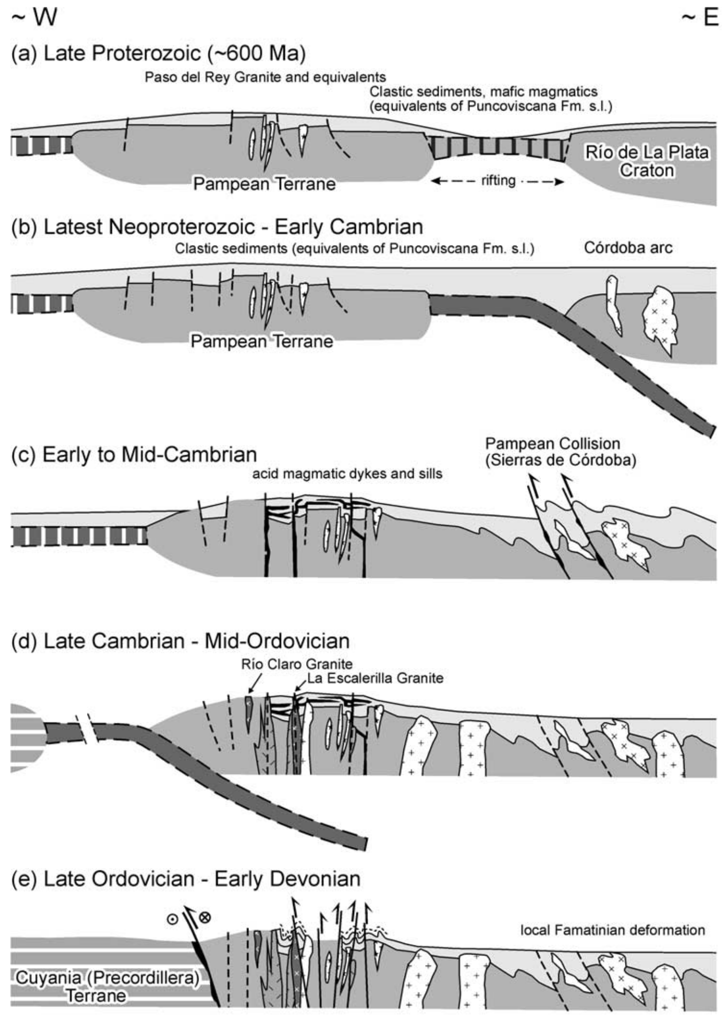

Fig. 6. Interpretative profile cartoons to illustrate the Precambrian to Early Paleozoic evolution of the Sierra de San Luis and surroundings (schematic and simplified sketches, not to scale). (a) Intrusion of Paso del Rey Granite and related granitoids in the Micaschist Group (equivalent of the Puncoviscana Formation s.l.) and basement of the Pampean Terrane. The latter is interpreted as a detached fragment of the Río de La Plata Craton in the east with the initial formation of an intervening rift basin. (b) Continuing clastic sedimentation of the Puncoviscana Formation s.l. equivalents. East-directed subduction beneath the Río de La Plata Craton due to eastward shift of the Pampean Terrane. (c) Collison between the Pampean Terrane and Río de La Plata Craton in the Sierras de Córdoba led to compression and metamorphism. In the western part of the collided terrane (Sierra de San Luis), injection of acid magmatic dykes and sills took place. (d) East-directed subduction beneath the Eastern Sierras Pampeanas with the formation of the Famatinian magmatic arc in the Sierra de San Luis. Tonalites, granodiorites, and granites intrude the clastic sedimentary pile. (e) Famatinian collision of the Cuyania (Precordillera) Terrane with the Eastern Sierras Pampeanas led to high-angle reverse faulting, folding, and shearing at least under greenschist facies metamorphic conditions. Local deformation in the Sierras de Córdoba can be related to this event (see text for further explanations).

ages of 1600–1700 Ma from intrusions of the southern sierras of the La Rioja Province, which suggests the existence of a mature crust different than the Grenvillian crust of the Cuyania (Precordillera) Terrane (Pankhurst et al., 1998).

The further evolution of the magmatic–metamorphic complex can be broadly separated into several stages, which are summarized in the principal sketches of Fig. 6. On a west-facing passive margin, a monotonous clastic turbidite succession (later Micaschist Group and Phyllite Group) was deposited (von Gosen and Prozzi, 1998). Sedimentation may have started prior to ~608 Ma and continued to Early Cambrian times.

It is noteworthy that equivalents of the Puncoviscana Formation s.l. extend from the western part of the Sierras de San Luis to the Sierras de Córdoba (Rapela et al., 1998a), supporting the existence of a large ‘Puncoviscana basin’ (or basins) along the western margin of the Río de La Plata Craton (Aceñolaza and Miller, 1982; Kraemer et al., 1995) during the Late Proterozoic–Early Cambrian time interval. This would suggest that the Pampean Terrane is not exotic or far-traveled but could represent a detached fragment of the Río de La Plata Craton (cf. Brito Neves and Cordani, 1991; Rapela et al., 1998a) as part of the Neoproterozoic West Gondwana supercontinent (see, e.g. Unrug, 1996, 1997; Trompette, 1997).

In northern Argentina, sedimentary transports in the Puncoviscana Formation s.l. indicate source areas in the east (Ježek and Miller, 1986; Ježek, 1990), which might have been the uplifted Brazilides in the interior of the Brazilian Shield (Ježek and Miller, 1987; Willner, 1987). Although comparable studies do not exist for the Sierra de San Luis and surroundings, a comparable sedimentary transport from eastern directions seems to be reasonable and would support a position of the Pampean Terrane near eastern cratonic areas.

Sedimentation during fragmentation could be represented by parts of the Micaschist Group that contain amphibolites (Fig. 6a). From the latter in the Sierra del Morro, east of the Sierra de San Luis, Delakowitz (1988) and Delakowitz et al. (1991a,b) have reported geochemical data suggesting a tholeiitic basaltic volcanism on continental crust, probably during an initial back-arc basin rifting. Ramos (1991) interpreted such a basin formation as related to island arcs in the west whose accretions formed the San Luis's basement during Proterozoic times.

It is noteworthy that, from the mafic/ultramafic complexes in the Eastern Basement Complex of the Sierra de San Luis, a tholeiitic trend has been proposed by Brogioni (1994) and Brogioni and Ribot (1994). They also assume a back-arc environment as a probable setting (Brogioni and Ribot, 1994; Malvicini and Brogioni, 1995), which is in contradiction with the interpretation of Early Famatinian intrusives during arc plutonism (Sims et al., 1998).

In the Sierras de Córdoba, geochemical studies of, for example, Mutti and Di Marco (1998) and Mutti et al. (1998) have shown the existence of an arc – back-arc system that they interpret to be of Neoproterozoic age. As stated by Rapela et al. (1998a), however, there is uncertainty in the geological significance of older isotopic data. They report amphibolite bodies with geochemical MORB signatures and suggest that ocean crust was involved with marine sediments in the passive margin. The existence of relicts of oceanic crust is also shown by Escayola et al. (1996).

The Paso del Rey Granite intruded the clastic succession (later micaschists) at ca. 608 Ma, presumably in thickened continental crust (Fig. 6a). It is possible that, prior to intrusion, the already deformed and metamorphosed Eastern Basement Complex had been lifted and juxtaposed against the sedimentary succession (later Micaschist Group). It is assumed that the Cruz de Caña and Cerros Largos granites are of comparable age, thus in support of the Proterozoic age of the Eastern Basement Complex.

If this scenario is correct, then the rifting of the Pampean Terrane from the Río de La Plata Craton may have started prior to ~608 Ma and therefore would roughly fall in the second young and short-lived tectonic Pan-African – Brasiliano cycle, as proposed by Trompette (1997). This could have been prior to, or in conjunction with, the break up of Laurentia from Amazonia, which is thought to have taken place before the end of the Proterozoic (cf. Hoffman, 1991; Torsvik et al., 1996; Unrug, 1996, 1997). Dalziel (1997) suggests that rifting of Laurentia from Gondwana took place near the Precambrian–Cambrian boundary.

Structures of a single deformational event in the micaschists of the Sierra de San Luis, prior to the first Famatinian deformation of the Phyllite Group rocks and intrusions, are interpreted as the effect of the Latest Proterozoic–Earliest Cambrian onset of deformation in the Pampean collisional belt in the east. From the western margin of the Pampean Terrane (Sierra de La Huerta), arc-related deformation in a comparable time interval is interpreted by Vujovich et al. (1994).

In the Sierra de San Luis, passive margin conditions prevailed at least up to the Early Cambrian (Fig. 6b). The coarse Cañada Honda conglomerate (Prozzi, 1990) can be interpreted as a fault scarp sediment related to syn-sedimentary block faulting during turbiditic sedimentation. No indications were found to postulate a back-arc setting for the monotonous clastic succession (Phyllite Group). During Early Cambrian times, the turbidite succession was injected by acid magmatic dykes and sills (rhyolites to dacites). Clasts of rhyolites within the Cañada Honda Conglomerate could have been derived from such intrusions.

As the injection of dykes and sills indicates overall crustal extension under brittle conditions, no clear equivalent of the collisional, Early to Mid-Cambrian Pampean event (Fig. 6c), described from the Sierras de Córdoba in the east (Rapela et al., 1998a), exists in the Sierra de San Luis. Thus, the Pampean Terrane, accreted to the Río de La Plata Craton in the east (Ramos, 1988; Rapela et al., 1998a,c), does not record clear evidence of Pampean compression in this segment of the western part during this time interval.

Prior to the onset of Famatinian arc magmatism, the Western Basement Complex of the Sierra de San Luis was lifted with respect to the clastic sedimentary pile in the east. Furthermore, faulting occurred in the later locality of the La Escalerilla Granite. The precise timing of displacement is unclear. It is possible, however, that faulting took place during Early Cambrian injection of the acid dykes and sills and may have continued to the Late Cambrian.

Famatinian arc plutonism began at ca. 500 Ma and continued to ca. 460 Ma. It can be related to east-directed subduction beneath the Eastern Sierras Pampeanas (former Pampean Terrane) due to an eastward shift of the Cuyania (Precordillera) Terrane (Fig. 6d). The emplacement of the intrusives often follows preexisting fault lines between the units. This suggests that, after the long period of clastic sedimentation at the west-facing passive margin, fault tectonics continued during Cambrian times. Even during the Late Cambrian–Mid-Ordovician active continental margin evolution of the Sierra de San Luis, these discontinuity planes were used by the upwelling magmas.

After arc plutonism had ceased, compression and regional metamorphism affected the former passive margin (Fig. 6e). The (undeformed) clastic (meta-) sediments and intrusions were deformed, at least under greenschist facies conditions. In the Sierra de San Luis, the contrast between the Basement Complexes, depicting a steeply inclined to subvertical older foliation overprinted by heterogeneous shearing, and the folded cover sediments is obvious. This difference reflects the former passive margin configuration of different blocks that subsequently were affected by compression. The timing of compressive deformation and metamorphism, related to the arrival and final collision of the Cuyania (Precordillera) Terrane, can be broadly assigned to the Late Ordovician–Early Devonian time interval.

7. Conclusions

The new isotopic data from intrusions of the Sierra de San Luis, combined with structural analyses and published data, enable the tentative interpretation of the following line of events in the metamorphic complex (Fig. 6):

(1) The Western and Eastern Basement Complexes of the sierra are of Proterozoic age. Their tectonic and metamorphic evolution can be related to the early stage of the Brasiliano-Pan-African orogeny or even older cycles.

(2) Proterozoic compression was followed by clastic sedimentation with the generation of mafic magmatics (later micaschists with amphibolites), probably under crustal extension. These deposits are interpreted as early equivalents of the Puncoviscana Formation s.l. (Fig. 6a), formed during rifting between the Río de La Plata Craton and the Pampean Terrane. At 608 + 26/−25 Ma, the Paso del Rey Granite intruded the clastic sediments. It can be roughly compared to either the Brasiliano I post-orogenic plutonism or the magmatic arc stage of the Rio Doce Orogeny in southeast Brazil (Campos Neto and Figueiredo, 1995).

(3) During Latest Neoproterozoic times, eastward-directed subduction beneath the Río de La Plata Craton may have started (Fig. 6b). Simple deformation and metamorphism of the micaschists with amphibolites and the Paso del Rey Granite took place prior to Famatinian arc plutonism and injection of Early Cambrian acid magmatic dykes and sills. It is assumed here that this event was Latest Proterozoic–Earliest Cambrian in age. By this, it could be an equivalent of the collisional stage of the Rio Doce Orogeny in southeast Brazil, which spans the 560–530 Ma interval (Campos Neto and Figueiredo, 1995). Hence, it indicates an early stage of Pampean compression, which culminated at ca. 530–520 Ma (Rapela et al., 1998c).

(4) Continuing clastic sedimentation in the upper parts of the crust, reflecting the large Puncoviscana basin at the western margin of the Río de La Plata Craton, came to an end during the Early Cambrian. Deposition was followed by injection of acid magmatic dykes and sills, probably under overall extension (Fig. 6c). From our present knowledge, we believe that these were the only effects of the Pampean collision in the Sierra de San Luis, even though it led to the accretion of the Pampean Terrane, including the Sierras de Córdoba (e.g. Rapela et al., 1998a), at the Río de La Plata Craton in the east.

(5) The passive margin setting with block faulting at the western margin of the Eastern Sierras Pampeanas changed to an active margin during the Late Cambrian–Early Ordovician. The Río Claro Granite and La Escalerilla Granite intruded the Western Basement Complex at 490 (±15) and 507 Ma (±24), respectively. The latter granite intruded also the Phyllite Group clastics. Both intrusions are part of the Famatinian magmatic arc in this segment of the western margin of Gondwana (Fig. 6d). Arc plutonism is related to east-directed subduction beneath the Eastern Sierras Pampeanas due to the eastward shift of the Cuyania (Precordillera) Terrane. It was followed by compressive deformation related to the collision of the terrane with the Eastern Sierras Pampeanas, which can only be estimated to have taken place in the Late Ordovician–Early Devonian time interval (Fig. 6e).

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Appendix A. Sample preparations and analytical procedures

The cleaned samples were processed in the Laboratories of the Munich* and Münster** Universities. They were crushed in a jaw breaker to a grain size <10 mm. Further grinding to a grain size <1 mm was done by a roll mill* or a disk mill**. The heavy minerals in the sieved fractions <0.18 mm* or <0.25 mm** were concentrated using a Wilfley-type wet shaking table. Further concentration of the zircons was achieved by the use of heavy liquids and a Frantz isodynamic separator. The La Escalerilla Granite (SL96-51*) zircon concentrate was subdivided into five grain size fractions for further selection of zircon fractions; the few high-quality zircons for single-grain analyses of all other samples were selected from the bulk sample. No air abrasion has been made.

A.1. Zircon fractions*

The hand-picked zircon fractions (50–200 grains) were cleaned in 3N HCl for 2 min in an ultrasonic bath at room temperature, followed by rinsing with aqua dest. and drying with acetone. Decomposition of the zircon fractions was performed in steel-cased teflon containers with 24N HF at 180 °C for 5–7 days. The concentrations of U and Pb were determined by the isotope dilution technique using a $^{235}U-^{208}Pb$ mixed spike. U and Pb were enriched by common step eluation ion exchange technique described by Krogh (1973). Long-term total laboratory blanks were about 30–130 pg Pb and corrected for the following laboratory blank composition: 6/4 = 18.15, 7/4 = 15.63, and 8/4 = 38.14* The composition of the inherited common Pb was estimated according to the lead evolution model of Stacey and Kramers (1975). Pb (IC and ID, respectively) was loaded with silica gel and phosphoric acid on a Re single filament and measured in a static mode on a Finnigan MAT 261 mass spectrometer at 1250–1300 °C, whereas U was loaded with aqua dest. on the Re evaporation filament of a double filament configuration and measured at 1950–2000 °C by peak hopping. Mass fractionation (0.13% per amu) has been controlled on each barrel by standard samples (NBS 982, U 500).

A.2. Single zircons**;

The hand-picked crystals were washed with 3.5N HNO_3 for 30 min at 80 °C, then rinsed with aqua dest. and dried with acetone. Decomposition of the individual crystals was made with 2 μl 24N HF in a steel cased multi-hole teflon container for 3–4 days at 180 °C. The decomposed zircon substrate was spiked with an appropriate amount (2 μl) of a $^{205}Pb-^{233}U$ tracer solution. After drying, the sample was converted to the chloride form with 2 μl of 6N HCl overnight. The dried sample was loaded with a mixture of silica gel, HCl, and phosphoric acid on a Re single filament. Measurement of U and Pb was performed on a VG 354 mass spectrometer equipped with a DALY multiplier and an ion-counting device by peak hopping. Pb was measured at 1250–1350 °C and U at 1400–1450 °C; mass fractionation was controlled by the measurement of the standards NBS 982 and U 500 (0.14% per amu). The maximum measured $^{206}Pb/^{204}Pb$ ratio during the course of the analyses was 1500, which is indicative of a rather negligible procedure blank. The calculations were corrected with maximum Pb blank of 5 pg with the following composition: 6/4 = 17.72, 7/4 = 15.52, and 8/4 = 37.7 and an U blank of 1 pg. The initial Pb composition was calculated according to the Pb evolution model of Stacey and Kramers (1975). All concordia calculations are based on Ludwig (1993) (Version 2.06a from 3 September 99; intercept errors are quoted at the 95% confidence level). Analytical data are given in Table 1.

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