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ORIGINAL PAPER

The tectonic significance of K/Ar illite fine-fraction ages from the San Luis Formation (Eastern Sierras Pampeanas, Argentina)

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Abstract The Sierra de San Luis forms the southern tip of the Eastern Sierras Pampeanas in central Argentina. Two narrow belts of low-grade phyllites and quartz arenites, i.e. the San Luis Formation, have accommodated part of the strain-related differential exhumation of the medium- to high-grade metamorphic domains that constitute to the basement complex of the sierra. Eleven phyllite samples were subjected to the K/Ar fine-fraction dating technique. Results are interpreted in relation to the Kübler index of the illites, which indicate epimetamorphic conditions for the majority of the samples. Obtained ages between 330 and 290 Ma cover a period of compressional tectonics in the late Mississippian (Visean/Serpukhovian boundary) followed by the subsidence during the formation of the Paganzo Basin in the provinces of La Rioja and San Luis. These tectonic movements are coincident with the Toco orogeny in northern Chile and southern Bolivia. This suggests that the older K/Ar ages document the compressional stage and that younger ages record the cooling of the basement during the subsequent extensional uplift of the basement.

Keywords Eastern Sierras Pampeanas · San Luis Formation · Paganzo Basin · K/Ar · Illite fine fractions

Introduction

Besides the understanding of structural and geochemical issues, the itemisation of the geodynamic history within polyphase-reactivated basement domains requires detailed geochronological information on the intrusive, metamorphic and deformational history. Constraints on the deformational history imply the knowledge on the textural relation of the dated mineral with its host rock. At high temperature conditions, potential candidates are kyanite, staurolite or garnet that have been shown to be suitable for stepwise lead leaching experiments (Frei and Kamber 1995), while in greenschist facies and lower-grade metamorphic conditions the Ar systematic in K-bearing minerals such as mica becomes of particular interest (e.g. Hunziker et al. 1986; Wemmer and Ahrendt 1997; Clauer and Chaudhuri 1998). In pelitic rocks, K-bearing white micas are formed by prograde dynamo-thermal metamorphic reactions that involve chlorite and illite minerals (Frey et al. 1980), whereas fluid-assisted retrogression of high-grade psammopelitic assemblages will result in phyllitic rocks.

The rheological properties of phyllitic rocks make them highly sensitive even to minor variations of the regional stress field. Hence, K/Ar dating on fine fractions of newly formed or recrystallised white micas can provide insight into the final reactivation of low-grade metamorphic shear

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zones (Weaver and Wampler 1970; Hunziker 1979; Kligfield et al. 1986; Wemmer 1991; Clauer et al. 1995; Zhao et al. 1997, 1999; Glasmacher et al. 2003 and references therein). The interpretation of the Ar systematic in illite crystals from low-grade shear zones has to be corroborated by X-ray diffraction–based calculation of the Kübler index, in order to distinguish between newly grown metamorphic crystals or detrital material (e.g. Reuter 1987; Reuter and Dallmeyer 1989; Ahrendt et al. 1991; Clauer and Chaudhuri 1998; Wemmer and Ahrendt 1997).

Within the metamorphic basement of the Sierras Pampeanas in central and northern Argentina, the amount of reliable K/Ar fine-fraction ages is of minor significance, even though low-grade metapelitic rocks are widespread. Attempts to date the metamorphic history of the Puncoviscana Formation in the northern parts of the Sierras Pampeanas were done by Adams et al. (1990). Ages between 540 and 535 Ma have been related to the Pampean deformation. Within the Sierra de Pocho, i.e. the northwestern range of the Sierras de Córdoba, Rapela et al. (1998) presented a single K/Ar age of 512 ± 19 Ma on the grain size fraction <0.5 μm that they interpreted as the metamorphic peak in the low-grade successions. K/Ar fine-fraction ages from the Sierras de Quilmes (Salta) in the range between 404–400 Ma (<2 μm) and 392–379 Ma (<0.2 μm) represent metamorphic retrogression and have been correlated with the lower limit of greenschist facies conditions (Büttner et al. 2005).

In the Sierra de San Luis, phyllitic rocks are associated with metaquartz arenites and volcanites (i.e. the San Luis Formation of Prozzi and Ramos 1988) forming the envelope of a medium- to high-grade metamorphic basement (Fig. 1, Sims et al. 1998; von Gosen 1998). The contact relationship between the San Luis Formation and the higher-grade metamorphic rocks in the centre of this basement complex, i.e. the Pringles Metamorphic Complex of Sims et al. (1998), is under controversial discussion (von Gosen 1998; Ortiz Suárez and Casquet 2005; Steenken et al. 2008), even though most of the descriptions indicate that the low-grade metapelitic sequences underwent a common D_2 folding event and metamorphism with those of higher grade at $\sim$470 Ma during the Famatinian tectonic cycle (Sims et al. 1998; Steenken et al. 2008).

In this paper, we present K/Ar mica fine-fraction ages from the phyllites of the San Luis Formation in the Sierra de San Luis. Fresh phyllitic material from eleven sample localities was subjected to K/Ar analysis and X-ray diffraction in order to define a minimum age for the deformation history of the phyllitic rocks under lower greenschist facies conditions. Previous efforts to date the timing of mylonitic deformation were carried out on mica separates from the more competent arenitic members of the low-grade successions yielding Ar/Ar ages of $\sim$360 Ma (Sims et al. 1998) corresponding to the Achalian event in the Sierra de San Luis. Age determinations of the last deformational event will help to delineate between the Achalian and the Toco tectonic events; the latter one was recognised up to now only in northern Chile and southern Bolivia (Bahlburg and Breitkreuz 1991). The presented results are considered within the frame of the regional tectonics acting on the southwestern margin of Gondwana.

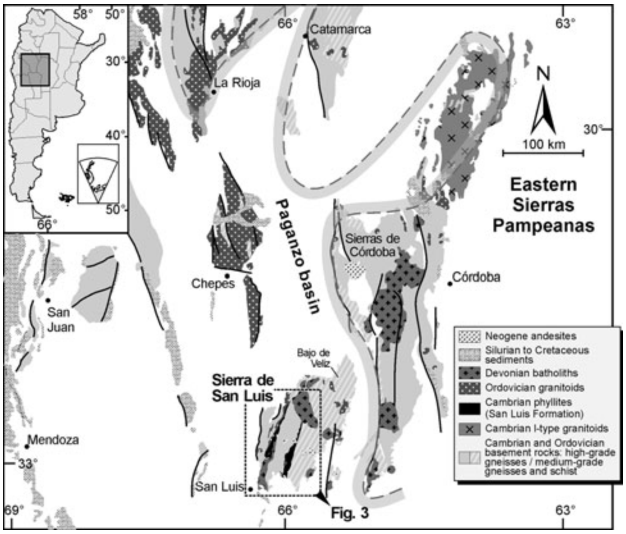

Fig. 1 Geological overview on the different basement domains of the Eastern Sierras Pampeanas in Argentina (Modified from von Gosen and Prozzi 1998, Martino 2003 and Steenken et al. 2004). The *dashed line* indicates the eastern margin of the Paganzo Basin. Ages for the metasedimentary sequences refer to the timing of metamorphism

Geological setting

The Eastern Sierras Pampeanas comprise the southern tip of the proto-Andean metamorphic basement outcropping in northern and central Argentina (Fig. 1, Caminos 1979). This basement has registered the polyphase accretional history in the east of the Río de La Plata craton starting in the early Cambrian with the collision of the Pampean Terrane with the craton (Ramos et al. 1986; Rapela et al. 1998; Stuart-Smith et al. 1999) followed by the amalgamation of the Precordillera/Cuyania Terrane to the newly formed margin of Gondwana during the Famatinian cycle (Astini and Thomas 1999; Rapalini et al. 1999; Casquet et al. 2001; Thomas et al. 2002; Astini and Dávila 2004; Steenken et al. 2006). The mode of emplacement of voluminous discordant granodioritic to syenogranitic batholiths throughout the Devonian is a matter of ongoing discussion. A post-tectonic emplacement with respect to the Famatinian cycle was favoured (Llambías et al. 1998; Pinotti et al. 2006), whereas the report of high-temperature shear zone fabrics provides evidence for their syntectonic emplacement (Siegesmund et al. 2004; López de Luchi et al. 2004). The latter supports the hypothesis of a separated Achalian tectonic cycle (Sims et al. 1998) probably related to the approach of the Chilenia Terrane (Ramos and Basei 1997). Relative tectonic quiescence commenced during the Late Devonian albeit subduction was active (Ramos et al. 1986). Extensional arc and retroarc basins formed from the Late Devonian on acted as recipients of alluvial and minor marine sediments (Limarino and Spalletti 2006). An interlude of compressional tectonics, the "Toco-orogeny", in the Late Mississippian is recognised in northern Chile and southern Bolivia (Bahlburg and Breitkreuz 1991). This compressional period is documented by a hiatus in the stratigraphic record between the Late Devonian/early Mississippian successions and the Pennsylvanian to Permian Paganzo Formation (Limarino and Spalletti 2006). Following this tectonic stage, the deposition of the Paganzo Formation commenced in the latest Mississippian overlaying unconformably the Angualasto group (Salfity and Gorustovich 1983; Azcuy et al. 1999). In proximity to the Andean Cordillera, the resumption of compression started by the late Cisuralian, the San Rafael phase during which rhyolitic volcanites of the Choiyoi Group were discordantly deposited on top of the Paganzo Formation (Mpodozis and Kay 1992).

Among the basement domains of the Eastern Sierras Pampeanas, the Sierra de San Luis forms the southernmost extreme (Fig. 1). Three NNE trending medium- to high-grade metamorphic domains of predominantly metaclastic composition have been recognised: those are from west to east the Nogolí, Pringles and Conlara Metamorphic Complexes (Sims et al. 1998). They are predominantly constituted by metapelites and metapsammites with layers of amphibolites and deformed crustal derived granites. Only in the Nogolí Metamorphic Complex, the appearance of large volumes of orthogneisses has been described (Ortíz Suárez et al. 1992; von Gosen and Prozzi 1998; Sims et al. 1998). In the central and southern part of the sierra, the basement domains are separated by the low-grade metamorphic sequences of the San Luis Formation (Fig. 1). Dominant tight fold structures developed during the metamorphic peak of the Famatinian cycle. NNE trending compressive shear zones located within the low-grade successions accommodated the displacement related to the differential exhumation of the basement domains. Macroscopic shear fabrics generally indicate an "east-side-up" displacement with a subordinated sinistral component (von Gosen 1998; Steenken et al. 2008). Besides phyllitic rocks and metaquartz arenites, the San Luis Formation comprises minor occurrences of acidic and intermediate metavolcanoclastic deposits (Hack et al. 1991; Ortíz Suárez et al. 1992; von Gosen 1998). Remarkable is the appearance of a concordant level of poorly sorted matrix-supported polymictic metaconglomerates in the central part of the eastern phyllite belt (Prozzi 1990) that have been interpreted as channel deposits. The San Luis Formation forms the host for a series of mainly tonalitic intrusions of crustal origin (López de Luchi et al. 2007). Those were syntectonically emplaced approximately between 480 and 470 Ma (Sims et al. 1998; Sato et al. 2005; Steenken et al. 2006) providing a minimum time constraint for the formation of the open to tight folds in the San Luis Formation, corresponding to D_2 event of the Famatinian cycle (Steenken et al. 2008). The best approximation for the time of deposition of the sequence is based on an U/Pb zircon age of 529 ± 12 Ma yielded from a corcordant volcanoclastic deposit (Söllner et al. 2000).

Several correlations of sedimentary succession of the San Luis Formation with the Puncoviscana Formation cropping out in the provinces of Salta, Jujuy and Tucumán have been proposed (Toselli 1990; Rapela et al. 1998; Söllner et al. 2000), although contrasting Nd systematics and whole-rock geochemistry do not support their common sedimentary history but denote a probable correlation of the Puncoviscana Formation with the Conlara Metamorphic Complex (Fig. 3) representing the eastern part of the sierra (Steenken et al. 2004; Zimmermann 2005). Major and trace elements of the San Luis Formation indicate an average upper crustal composition typical for shales, whose deposition took place either in a continental island arc or in an active margin setting (López de Luchi et al. 2003). A recent compilation of various geochemical data of all basement units of the Sierra de San Luis and the Puncoviscana Formation of the Cordillera Oriental is given in Drobe et al. (2009).

Structural and petrological observation

The NNE trending low-grade metamorphic phyllites and quartz-arenites of the San Luis Formation appear in two belts of approximately 55 km length and a width of up to 5 km, forming the metasedimentary envelope of the medium- to high-grade metamorphic successions of the Pringles Metamorphic Complex. The structural relationship between the different basement units is under controversial discussion (von Gosen and Prozzi 1998; von Gosen 1998; Sims et al. 1998; Steenken et al. 2008). SHRIMP and conventional U/Pb age constraints suggest that the entire sequence was deposited following the Pampean orogeny (Steenken et al. 2006). Gradual structural and petrological transitions between the differentially metamorphosed sequences of the Pringles Metamorphic Complex (including the San Luis Formation—Steenken et al. 2004) were observed (von Gosen 1998) if not obliterated as in the southwest of the sierra by younger intrusive rocks like the

La Escalerilla batholith (Sims et al. 1998; Fig. 1). Large-scale tight folds with NNE trending and moderately plunging axes were described as belonging to the first deformation of the San Luis Formation (Fig. 2a) corresponding to the Famatinian D2 event recorded by other basement domains of the Sierra (von Gosen 1998; Steenken et al. 2008). However, the local appearance of isoclinally folded quartz layers within the phyllites (Fig. 2b) suggests a preceding folding phase equivalent to the Famatinian D1 deformation. Differences in the structural record do not necessarily result from deformation offset and coverage by new sediments but may be addressed also to the different rheological properties at different crustal levels during deformation (Steenken et al. 2008).

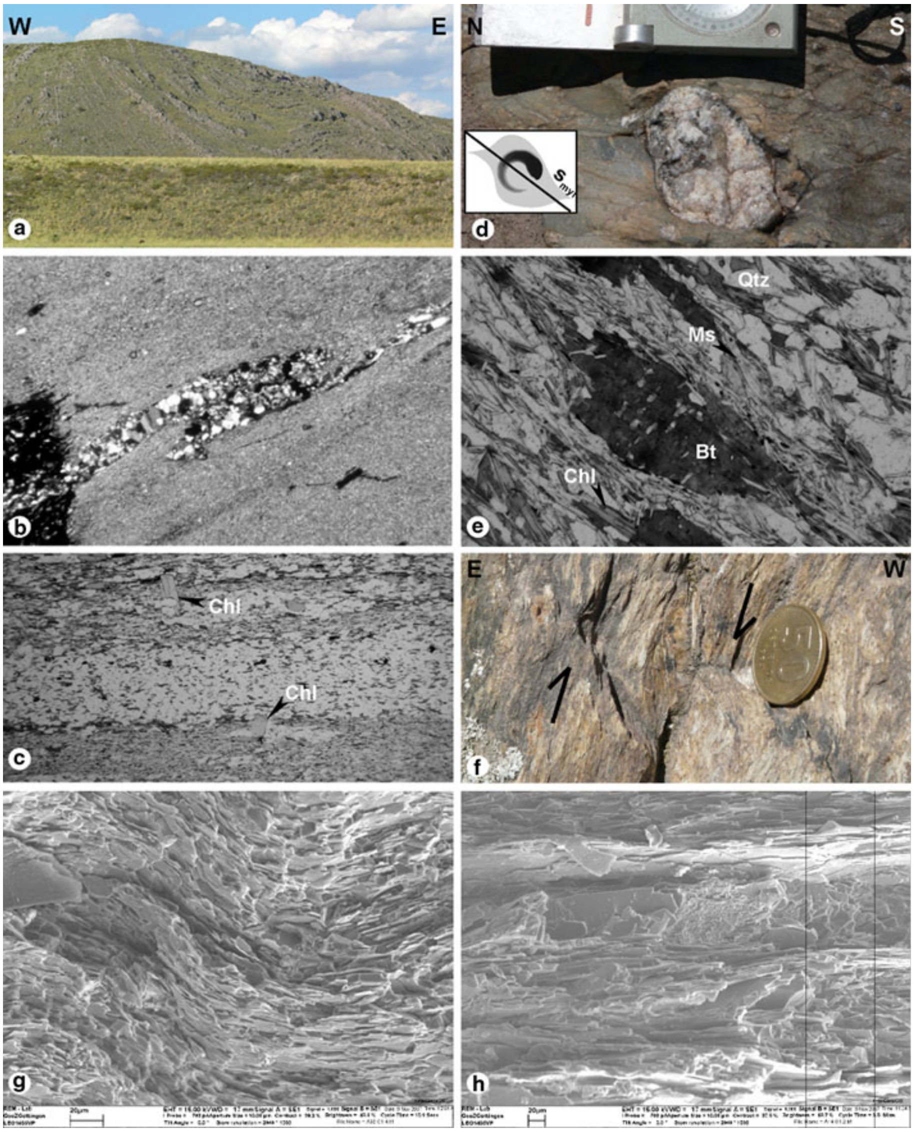

Fig. 2 Field and microscopic aspects of the San Luis Formation. **a** *Open fold* structures of the San Luis Formation corresponding to the Famatinian D2 event (width of view ~300 m). **b** Isoclinal intrafolial fold of a quartz layer suggestive of the presence of a D1 folding phase in the San Luis Formation. Strain-free quartz crystals with high-angle grain boundaries are developed (width of view: 2.5 mm). **c** Fine-grained phyllite with quartz, biotite and chlorite. Large chlorites frequently enclose high angles with the S_1 foliation (parallel polarised light, width of view: ~21 mm). **d** *S–C* shear indicator showing the near vertical displacement of the Conlara metamorphic complex against the San Luis Fm. **e** Microscopic aspect of a biotite-bearing phyllite variety indicating lower greenschist facies conditions. Large biotite porphyroblasts that are parallel to the S_1 fabric made up by chlorite, illite (Ms) and quartz (parallel polarised light, width of view: ~0.5 mm). **f** Conglomerate clast in incipient rotation indicating a dextral sense of shear. **g, h** SEM images from the eastern belt of the San Luis Formation. A 32-01 (**g**) is the southern end whereas A 14-01 (**h**) marks the *northern end*. Both images are perpendicular to the cleavage *plane*. In the *right image* (**h**), the various cleavage *planes* indicate that the sample was polyphase deformed. This deformation is shown in the *left image* (**g**) only as the wide bending of the sericite *planes*

In general, the mineralogy of the phyllites of the San Luis Formation comprises illite + chlorite + biotite + quartz ± albite. Ubiquitous biotite with a diameter of up to 1 mm documents a minimum temperature of 400°C during its formation (Nitsch 1970) characterising lower greenschist facies metamorphism (Fig. 2e). Even higher metamorphic conditions may be indicated by the local presence of small garnets, which usually crystallise at temperatures >450°C as long as no Mn is present stabilising the garnet at lower temperature (Bucher and Frey 1994). Accessory minerals are tourmaline and ore minerals. The schistosity plane is frequently patched with needle-shaped chlorite crystals of less than 2 mm length. Within the proximity to the tonalitic intrusions, the phyllites have turned into hornfels with relict sericite-chlorite ± biotite aggregates suggesting the former existence of andalusite (von Gosen 1998).

The phyllites exhibit a pervasive alignment of micas and flattened quartz (Fig. 2c). Intracrystalline deformation of the quartz is indicated by parallel subgrain boundaries although contacts between larger crystals show triple junctions of 120°. Only in the vicinity of the tonalitic intrusions, a non-oriented growth of illite and biotite is observed related to contact metamorphism.

The eastern belt of the San Luis Formation hosts the transpressional Río Guzmán shear zone that accommodated the “east-side-up” displacement of the Conlara Metamorphic Complex. S–C fabrics document this vertical displacement (Fig. 2d). Steeply dipping stretching lineations on the NNE-SSW striking mylonitic foliation are south plunging indicating a minor sinistral component (von Gosen 1998; Steenken et al. 2008). However, the tectonic activation of the basement was not uniform since normal faulting with a dextral component has been reported from the conglomerate layers in the eastern belt of the succession (Fig. 2f, Martino et al. 2005). This extensional movement was associated with the formation of a discontinuous planar fabric that is characterised by chlorite (Fig. 2c).

Within the western belt, the “east-side-up” displacement is consistent with the vertical displacement that is recorded by the La Arenilla shear zone, which is located in the eastern part of the Pringles Metamorphic Complex (Ortíz Suárez et al. 1992; Hauzenberger et al. 2001).

Sample description

In order to access the latest stages of the Palaeozoic deformation within the Sierra de San Luis, eleven samples of the phyllitic sequences of the San Luis Formation have been subjected to the K/Ar fine-fraction dating technique (cf. Wemmer 1991). Of those samples, eight were taken from the eastern belt, whereas the other three represent the western belt of the San Luis Formation (Fig. 3). The sampling style avoided the contact metamorphic overprinted areas around the tonalitic intrusions. All samples are of pelitic grain size and show a closely spaced schistosity (Fig. 2g, h). The schistosity planes have a silver-grey gloss whereas perpendicular to the planar fabric the phyllites appear in an overall grey. The alternation between pure pelitic layers and more psammitic layers at the mm to cm scale is documented by the variation in colour intensity from dark grey to medium grey, respectively. SEM images from samples of the eastern belt of the San Luis Formation (Samples A 14-01 and A 32-01) are shown in Fig. 2g, h. Both images taken perpendicular to the foliation display various cleavage planes indicating a polyphase deformational history. The tight and even composition of the cleavage planes is in good agreement with epimetamorphic conditions. No indication for a lower-grade overprint, e.g. irregular growth of illite, has been observed. Microscopically identified minerals are illite, chlorite, biotite and quartz. Additionally, the presence of albite is documented by X-ray diffraction in the samples A 14-01, A 17-01, A 30-01, A 31-01, A 32-01 and AH 5 (Table 1). Garnet appears in sample A 30-01.

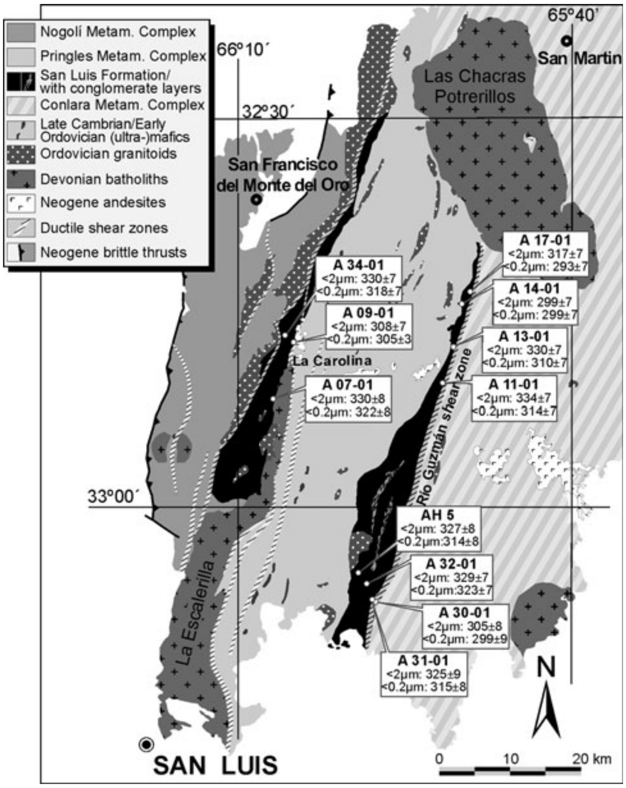

Fig. 3 Geological overview of the southwestern portion of the Sierra de San Luis (modified after von Gosen 1998 and Steenken et al. 2006). Sample locations and results of K/Ar age analyses

Table 1 Results of X-ray diffraction analyses

Sample	Illite	Chlorite	Quartz	Albite
A 7-01	++	+	o	−
A 9-01	++	++	o	−
A 34-01	++	++	o	−
A 11-01	++	++	o	−
A 13-01	++	++	o	−
A 14-01	++	++	o	o
A 17-01	++	++	o	o
A 30-01	+	++	+	+
A 31-01	++	++	+	+
A 32-01	++	++	o	−
AH 5	++	++	+	+

++ Principal component

\+ Abundantly present, o appears in traces only

− Not identified

Data acquisition

About 2 kg of previously washed sample material was crushed and ground in a shatter mill for 13–18 s until no graininess is registered by manual examination (Reuter 1985). The grain size fraction of <2 μm was gained by differential settling (Atterberg method) of the sieve fraction <63 μm. Enrichment of the grain size fraction <0.2 μm was carried out by ultracentrifugation (Wemmer 1991). The two grain size concentrates were subjected to isotope measurements as well as X-ray diffraction.

Kübler index (illite crystallinity)

The Kübler index was determined using a Phillips PW 1800 X-ray diffractometer. Texture compounds were prepared using 1.5–2.5 mg/cm^2 of sample material (Weber 1972). The metamorphic grade has been inferred from the peak width at half height of the 10-Å peak (Kübler 1967) using the software algorithm IDEE provided by the University of Göttingen (Friedrich 1991). Digital measurement was taken by a step scan: 301 points, 7–10° 2Θ, scan step 0.010° 2Θ, integration time 4 s, receiving slit 0.1 mm, automatic divergence slit. The crystallinity values may range from 0.060° Δ2ΘCuKα for ideally ordered muscovite to >1° Δ2ΘCuKα for illite/smectite mixed layers (Ahrendt et al. 1991; Wemmer 1991). Limits between the fields of diagenesis, anchi- and epizone are given by ~0.420° Δ2ΘCuKα and 0.250° Δ2ΘCuKα, respectively (Kübler 1967; Marheine 1997). The presence of mixed layer clays that may obliterate the 10-Å peak has been tested by duplicate determination of the material under air-dried and glycolated conditions.

Mineralogy of grain size fraction

In a follow-up session, X-ray diffraction was extended to the range from 4° to 70° 2Θ in order to estimate the mineral phases present in the sample material and to rule out the possible interference of other K-bearing minerals (e.g. K-feldspar) in the isotope analysis (Table 1).

K/Ar analyses

The argon isotopic composition was measured in a Pyrex glass extraction and purification line coupled to a VG 1200 C noble gas mass spectrometer, operating in static mode. The amount of radiogenic ^{40}Ar was determined by isotope dilution method using a highly enriched ^{38}Ar spike from Schumacher, Bern (Schumacher 1975). The spike was calibrated against the biotite standard HD-B1 (Fuhrmann et al. 1987). The age calculations are based on the constants recommended by the IUGS quoted in Steiger and Jäger (1977).

Potassium content was determined in duplicate by flame photometry using an Eppendorf Elex 63/61. The samples were dissolved in a mixture of HF and HNO_3. CsCl and LiCl were added as an ionisation buffer and internal standard, respectively. The analytical error for the K/Ar age calculations is given at a 95% confidence level (2σ). Analytical results are presented in Table 2. Details of argon and potassium analyses for the laboratory in Göttingen are given in Wemmer (1991).

Results

The Kübler index of all analysed samples varies from 0.145 ± 0.005° Δ2ΘCuKα to 0.285 ± 0.005° Δ2ΘCuKα. The minor differences in the Kübler index between the glycolated and the air-dried measurements are not significant; therefore, the presence of retrogradely grown mixed layer clays can be excluded (Table 2). All but three obtained values are indicative for epimetamorphic conditions (<0.250° Δ2ΘCuKα). In case of sample A 30-01, anchimetamorphic conditions are indicated, whereas the samples A 7-01 and A 14-01 mark the limit between epi- and anchimetamorphic conditions (Fig. 4). No systematic variation with respect to sample localities has been observed. Samples A 14-01 and A 30-01 belong to the northern and southern ends of the eastern belt of the San Luis Formation, whereas the sample A 7-01 was taken in the immediate west of the La Escalerilla batholith. Epimetamorphic conditions of around 300–350°C are insufficient to allow the growth of the observed small biotite and local garnet crystals, requiring a temperature of 400°C (lower greenschist facies). Temperatures as high as 400°C

Table 2 Compilation of the K/Ar ages and the Kübler Index of mineral fine fractions of <2 and <0.2 µm

Sample	Grain fraction (µm)	K/Ar data					Illite crystallinity	
		K_2O (wt. %)	$^{40}Ar^*$ (nl/g) STP	$^{40}Ar^*$ (%)	Age (Ma)	±2σ-error (Ma)	Air dry Δ°2θ	Glycolated Δ°2θ
A 7-01	<0.2	4.23	48.11	86.28	322.1	8.0	0.250	0.250
	<2	4.46	52.01	86.79	329.6	8.2	0.245	0.250
A 9-01	<0.2	2.92	31.41	83.45	304.9	7.8	0.170	0.175
	<2	3.11	33.64	84.84	307.6	7.3	0.170	0.170
A 34-01	<0.2	4.08	45.78	95.23	318.3	7.1	0.165	0.165
	<2	4.41	51.53	94.06	330.2	7.0	0.170	0.160
A 11-01	<0.2	4.53	50.08	91.87	313.9	6.8	0.150	0.155
	<2	5.88	69.66	94.58	334.4	7.1	0.150	0.155
A 13-01	<0.2	2.11	23.01	84.00	310.0	7.4	0.245	0.250
	<2	3.27	38.17	90.73	329.8	7.3	0.250	0.250
A 14-01	<0.2	4.58	47.97	86.55	298.6	7.4	0.160	0.190
	<2	4.63	48.58	86.81	299.1	7.0	0.180	0.195
A 17-01	<0.2	2.67	27.43	81.29	293.4	7.2	0.275	0.280
	<2	4.06	45.31	88.47	316.6	7.2	0.285	0.275
A 30-01	<0.2	2.44	25.58	71.85	298.9	9.5	0.190	0.175
	<2	2.43	26.00	73.99	304.6	8.3	0.195	0.180
A 31-01	<0.2	5.37	59.52	91.27	314.6	7.8	0.170	0.150
	<2	5.29	60.65	81.19	324.5	8.5	0.170	0.155
A 32-01	<0.2	5.99	68.33	94.06	323.0	7.2	0.170	0.145
	<2	6.16	71.65	90.09	328.8	7.4	0.175	0.150
AH 5	<0.2	4.57	50.62	83.31	314.4	7.8	0.170	0.170
	<2	4.57	52.84	85.22	327.0	7.7	0.170	0.170

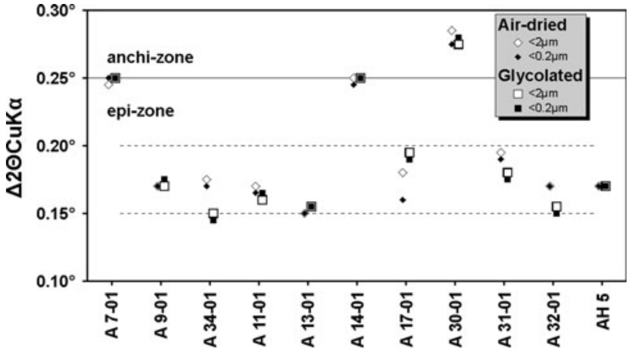

Fig. 4 *Chart* showing the Kübler Index measured for the analysed samples. Similarity between 'air-dried' and 'glycolated' experiments is indicative for the absence of mixed layer clays

will certainly erase any detrital memory in the investigated fine fractions, and the gained age information has to be interpreted in terms of a post-peak metamorphic deformational reactivation of the phyllites. Additionally, the mineralogical composition gained from the X-ray diffraction does not indicate any other potassium- or calcium-bearing mineral phase that would disturb the isotope system.

K/Ar ages of the two grain size fractions, i.e. <2 and <0.2 µm, are in the range from 334.4 ± 7.1 to 299.1 ± 7.0 Ma and 323.0 ± 7.2 to 293.4 ± 7.2 Ma (2σ), respectively. The weighted means for the two fractions are at 321.1 ± 7.5 and 310.2 ± 7.6 Ma. Comparing the ages of both fractions within the same sample reveals an age gap of ~20 Ma in only three samples (A 11-01, A 13-01 and A 17-01), whereas for the majority of the samples the two obtained ages overlap within error yielding a maximum difference of 13 Ma. Such a distribution can be explained in terms of an undisturbed deformational and metamorphic history. If larger differences between the two analysed fractions would appear, two scenarios could be discussed: (i) a detrital component in the <2 µm fraction leading to older ages or (ii) a weak retrograde overprint resulting in higher diffusion in the <0.2 µm fraction (Hess et al. 1993, Glasmacher et al. 2001) and a rejuvenation of the K/Ar ages. Both scenarios can be excluded. Gradual differences in the ages between the western and eastern belt of San Luis Formation can be seen (Fig. 5). A correlation of the younger K/Ar results with the Kübler Index of the anchimetamorphic values is apparent in samples A 14-01 and A 30-01.

Discussion

The interpretation of the K/Ar illite fine-fraction ages depends largely on the understanding of the closure

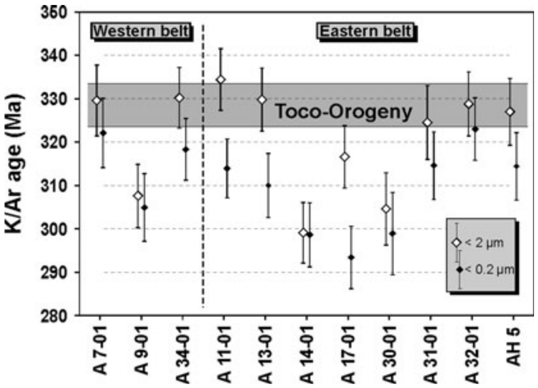

Fig. 5 Results from K/Ar analyses for the western and eastern belt of the San Luis Formation. Results can be interpreted in relation to the hiatus between the Late Devonian/early Mississippian Angualasto group and the late Mississippian to Permian Paganzo Formation caused by the Toco orogeny

behaviour of the small illite crystals. The importance of the effective diffusion radius on the closure temperature for the Ar system has been demonstrated throughout a large number of publications (Dahl 1996; Villa 1998; Hodges 2003). These publications focused on white micas with grain sizes >1 mm. In case of K/Ar fine-fraction ages, the available information is limited. Hunziker et al. (1986) reported a closure temperature interval for the mica fractions <2 µm of 260 ± 30°C. Wemmer and Ahrendt (1997) reported Cretaceous K/Ar ages on fine-grained white mica (sericite <2 µm) from the bottom of the German Deep Drilling Bore Hole (KTB). Here, in situ temperatures of 275°C did not reset the Ar system in the <2 µm serecites. Therefore, the closure temperature has to be estimated somewhere between 275–350°C for grain size fractions <2 µm, being somewhat lower than the closure temperature interval of 350 ± 50°C for coarse grained muscovite recommended by Purdy and Jäger (1976) and McDougall and Harrison (1999). Extensive discussion on the problems related to isotopic closure is given in Villa (1998).

The post-metamorphic cooling history of the different basement domains has been previously accessed by K/Ar dating on micas of various grain sizes (Varela et al. 1994; Sims et al. 1998; González and Sato 2000; Sosa et al. 2002; Steenken et al. 2004, 2008). Those results suggest that the cooling front as it is recorded by the Ar system in biotite commenced in the Nogolí Metamorphic Complex from where it migrated to the east. The recorded differences are small and it appears that the entire Sierra de San Luis has reached epimetamorphic conditions during the Middle Mississippian (345–328 Ma, ISC 2009). The internal distribution of the K/Ar ages suggests that the differential cooling of the metamorphic complexes (Nogolí, Pringles and Conlara) was not the result of a rotational *'en-bloc'* exhumation but rather accommodated by the two belts of the San Luis Formation (Steenken et al. 2008). It appears plausible that part of this adjustment is recorded by the new K/Ar fine-fraction ages covering the time-span from the Middle Mississippian to the lowermost Cisuralian (345–299 Ma, ISC 2009).

The K/Ar fine-fraction age of 512 ± 19 Ma from the nearby Sierra de Pocho presented by Rapela et al. (1998) marks final steps of the Pampean orogeny. It is much older than the new results of ~330 Ma for the Sierra de San Luis, indicating that despite the close proximity of the two tectono-morphological terrains the late Palaeozoic history took place independently.

The new K/Ar illite fine-fraction ages (>320 Ma) are synchronous with a widespread period of intra-Carboniferous tectonism, e.g. the Toco orogeny of Bahlburg and Breitkreuz (1991). The younger ages correspond to stratigraphic ages known from the Paganzo Basin, which shows an almost continuous stratigraphic record from the latest Upper Mississippian (318 Ma, ISC 2009) to the late Permian (251 Ma, ISC 2009) in the vicinity of the Eastern Sierras Pampeanas. In this area, the Paganzo Basin extends from the cities of Catamarca down to San Luis (cf. Fig. 1, Salfity and Gorustovich 1983; Azcuy et al. 1999). The eastern limit of the basin largely follows the present-day eastern footwall of the Sierras de Córdoba. Relicts of this retro arc basin in the Sierra de San Luis are recognised in the Bajo de Veliz, a NNE-trending graben in the north-easternmost tip of the Sierra. Stratigraphic ages reported by Salfity and Gorustovich (1983) for the Bajo de Veliz Formation start at the Upper Pennsylvanian, (303 Ma, ISC 2009). Deposition of the Paganzo Formation was contemporary with the shallow-level emplacement of plutonic rocks in the metasedimentary cover of the Chilenia Terrane (Mendoza Province) due to the ongoing subduction along the western outboard of Gondwana (Azcuy et al. 1999).

According to these stratigraphic findings, it is suggested that the K/Ar fine-fraction ages have recorded the Upper Mississippian (328–318 Ma, ISC 2009) tectonic phase that led to the hiatus in the stratigraphic record between the Late Devonian/early Mississippian Angualasto Group and the Paganzo Formation whose deposition started in the latest Mississippian (Limarino and Spalletti 2006). The younger ages of the archived spectra are the result of cooling during the subsidence of the Paganzo Basin. Normal faulting with dextral oblique component has been documented for the conglomeratic layers in the eastern phyllite belt (Martino et al. 2005).

K/Ar fine-fraction ages in a similar range from 320 to 290 Ma have been reported for the Cordillera Oriental in southern Bolivia close to the Argentinean border, i.e. the Chaco-Tarija Basin (Jacobshagen et al. 2002). This foreland basin (Isaacson and Díaz Martínez 1995) developed in the east of the east-verging belt of the Toco orogeny

(Bahlburg and Breitkreuz 1991) stressing the importance of this intra-Carboniferous event for the geodynamic history of the proto-Andean belt of southern South America. However, from a palaeotectonic point of view, the Upper Mississippian tectonism is poorly understood. A relation to the accretion of the Chilenia terrane has been proposed (Ramos et al. 1986; Gohrbandt 1992; Davis et al. 2000; Ramos 2001). This hypothesis contradicts the hypothesis of an Early Devonian docking of the Chilenia terrane to the southwestern margin of Gondwana (Sims et al. 1998; Siegesmund et al. 2004).

Conclusion

The K/Ar fine-fraction dating technique provides a powerful tool in the analysis of polyphase-reactivated basement domains. In the case of the Eastern Sierras Pampeanas in Argentina, the tectono-metamorphic record started in the early Palaeozoic and lasted until the extensional formation of the Paganzo Basin.

The final placement of the different basement domains of the Sierra de San Luis is recorded by K/Ar fine-fraction ages ranging from ~330 to 290 Ma. Ages >320 Ma correspond to a phase of compressional tectonism recognised as the Toco orogeny in northern Chile and southern Bolivia. Younger ages are the result of the subsequent subsidence of the basement consistent with the stratigraphic record of the Paganzo Basin. Evidence for the extension of this basin within the Sierra de San Luis is found in the graben structure of the Bajo de Veliz where sedimentation commenced during the Upper Pennsylvanian (307–299 Ma, ISC 2009).

The 320–290 Ma K/Ar fine-fraction ages from the Cordillera Oriental in the southern extreme of Bolivia (Chaco-Tarija basin, Jacobshagen et al. 2002) together with the set of data presented here put emphasis on the importance of compressional tectonism during the Pennsylvanian and Cisuralian in the proto-Andean basement of southern South America.

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References

Adams C, Miller H, Toselli A (1990) Nuevas edades de metamorfismo por el método K-Ar de la Formación Puncoviscana y Equivalentes, NW de Argentina. In: Aceñolaza F, Miller H, Toselli AJ (eds) El Ciclo Pampeano en el Noroeste Argentino. Serie Correlación Geológica No 4: 209–219

Ahrendt H, Hess JC, Wemmer K (1991) K/Ar-Altersdatierung an authigenen Illiten des Gasfeldes Thönse. Norddeutsche Akademie Geowissenschaftlicher Veröffentlichungen 6:108–114

Astini RA, Dávila FM (2004) Ordovician back arc foreland and Ocloyic thrust belt development on the western Gondwana margin as a response to Precordillera terrane accretion. Tectonics 23, doi:10.1029/2003TC001620

Astini RA, Thomas WA (1999) Origin and evolution of the Precordillera terrane of western Argentina: a drifted Laurentian orphan. In: Ramos VA, Keppie JD (eds) Laurentia–Gondwana Connections before Pangea. Geological Society of America, Special Papers 336:1–20

Azcuy CL, Carrizo HA, Caminos R (1999) Carbonífero y Pérmico de las Sierras Pampeanas, Famatina, Precordillera, Cordillera Frontal y Bloque de San Rafael. In: Caminos R (ed) Geología Regional Argentina, Anales 29:261–318

Bahlburg H, Breitkreuz C (1991) Paleozoic evolution of active margin basins in the southern Central Andes (northwestern Argentina and northern Chile). J South Am Earth Sci 4:171–188

Bucher K, Frey M (1994) Petrogenesis of metamorphic rocks, 6th edn. Springer, Berlin

Büttner SH, Glodny J, Lucassen F, Wemmer K, Erdmann S, Handler R, Franz G (2005) Ordovician metamorphism and plutonism in the Sierra de Quilmes metamorphic complex: implications for the tectonic setting of the northern Sierras Pampeanas (NW Argentina). Lithos 83:143–181

Caminos R (1979) Sierras Pampeanas Noroccidentales Salta, Tucumán, Catamarca, La Rioja y San Juan. 2° Simposio en Geología Regional Argentina, Academía Nacional de Ciencias de Córdoba 1:225–291

Casquet C, Baldo E, Pankhurst RJ, Rapela CW, Galindo C, Fanning CM, Saavedra J (2001) Involvement of the Argentine Precordillera terrane in the Famatinian mobile belt: U–Pb SHRIMP and metamorphic evidence from the Sierra de Pie de Palo. Geology 29:703–706

Clauer N, Chaudhuri S (1998) Isotopic dating of very low-grade metasedimentary and metavolcanic rocks: techniques and methods. In: Frey M, Robinson D (eds) Low-grade metamorphism. Blackwell Science, Cambridge UK, pp 202–226

Clauer N, Rais N, Schaltegger U, Piqué A (1995) K–Ar systematics of clay-to-mica minerals in a multi-stage low-grade metamorphic evolution. Chem Geol 124:305–316

Dahl PS (1996) The crystal–chemical basis for Ar retention in micas: inferences from interlayer partitioning and implications for geochronology. Contributions Mineral Petrol 123:22–39

Davis JS, Roeske SM, Mc Clelland WC, Snee LW (2000) Closing the ocean between the Precordillera terrane and Chilenia: early Devonian ophiolite emplacement and deformation in the SW Precordillera. In: Ramos VA, Keppie JD (eds) Laurentia–Gondwana Connections before Pangea. Geological Society of America, Special Papers 336:115–138

Drobe M, López de Luchi MG, Steenken A, Frei R, Naumann R, Siegesmund S, Wemmer K (2009) Provenance of the Late Proterozoic to Early Cambrian metaclastic sediments of the Sierra de San Luis (Eastern Sierras Pampeanas) and the Cordillera Oriental, Argentina. J South Am Earth Sci 28:232–262

Frei R, Kamber BS (1995) Single mineral Pb–Pb dating. Earth Planet Sci Lett 129:261–268

Frey M, Teichmüller M, Teichmüller R, Mullis J, Künzi B, Breitschmid A, Gruner U, Schwizer B (1980) Very low-grade metamorphism in external parts of the Central Alps: illite crystallinity, coal rank and fluid inclusion data. Eclogae Geologicae Helvetiae 73:173–203

Friedrich D (1991) Eine neue Methode zur Bestimmung der Illitkristallinität mit Hilfe digitaler Messwerterfassung. Unpublished diploma thesis, University of Göttingen, pp 1–63

Fuhrmann U, Lippolt HJ, Hess JC (1987) Examination of some proposed K–Ar standards: $^{40}Ar/^{39}Ar$ analyses and conventional K–Ar data. Chem Geol (Isot Geosci Sect) 66:41–51

Glasmacher UA, Tschernoster R, Clauer N, Spaeth G (2001) K–Ar dating of magmatic sericite crystallites for determination of cooling paths of metamorphic overprints. Chem Geol 175:637–687

Glasmacher UA, Tremblay A, Clauer N (2003) K–Ar dating constraints on the tectonothermal evolution of the external Humber zone, southern Quebec Appalachians. Can J Earth Sci 40:285–300

Gohrbandt KH (1992) Paleozoic paleogeographic and depositional developments on the central proto-Pacific margino of Gondwana. J South Am Earth Sci 6:267–287

González PD, Sato AM (2000) Los plutones monzoníticos cizallados El Molle y Barroso: Dos nuevos intrusivos pos-orogénicos en el oeste de las sierras de San Luis, Argentina. IX Congreso Geológico Chileno (Puerto Varas). Actas 1, 621–625 (Santiago, Chile)

Hack M, Brodtkorb de MK, Höll R, Brodtkorb A (1991) Geología y consideraciones geneticas de los yacimientos scheelíticos entre el dique La Florida y Pampa del Tamboreo, provincia de San Luis. In: Brodtkorb de MK (ed) Geología de yacimientos de wolframion de las provincias de San Luis y Córdoba, Argentina. Publicación del Instituto de Recursos Minerales No 1. Universidad Nacional de La Plata 113–152

Hauzenberger C, Mogessie A, Hoinkes G, Felfernig A, Bjerg E, Kostadinoff J, Delpino S, Dimieri L (2001) Metamorphic evolution of the Sierras de San Luis, Argentina: granulite facies metamorphism related to mafic intrusions. Mineral Petrol 71:95–126

Hess JC, Lippolt HJ, Gurbanov AG, Michalski I (1993) The cooling history of the late Pliocene Eldzhurtinskiy granite (Caucasus, Russia) and the thermochronological potential of grain-size/age relationships. Earth Planet Sci Lett 117:393–406

Hodges KV (2003) Geochronology and thermochronology in orogenic systems. In: Rudnick RL (ed) Treatise on geochemistry: the crust, vol 3. Amsterdam, Elsevier Science, pp 263–292

Hunziker JC (1979) Potassium-argon dating. In: Jäger E, Hunziker JC (eds) Lectures in isotope geology. Springer, New York, pp 52–76

Hunziker JC, Frey M, Clauer N, Dallmeyer RD, Friedrichsen H, Flehmig W, Hochstrasser K, Roggwiler P, Schwander H (1986) The evolution of the illite to muscovite: mineralogical and isotopic data from the Glarus Alps, Switzerland. Contr Mineral Petrol 92:157–180

Isaacson PE, Díaz Martínez E (1995) Evidence for a middle–late Paleozoic foreland basin and significant paleolatitudinal shift, Central Andes. In: Tankard AJ, Suarez SR, Welsink HJ (eds) Petroleum Basins of South America. American Association of Petroleum Geologists, Memoirials 62:231–249

ISC (2009) International Stratigraphic Chart, International Commission on Stratigraphy. http://www.stratigraphy.org/upload/ISChart2009.pdf

Jacobshagen V, Müller J, Wemmer K, Ahrendt H, Manutsoglu E (2002) Hercynian deformation and metamorphism in the Cordillera Oriental of Southern Bolivia, Central Andes. Tectonophysics 345:119–130

Kligfield R, Hunziker J, Dallmeyer RD, Schamel S (1986) Dating of deformation phases using the K–Ar and $^{40}Ar/^{39}Ar$ techniques: results from the Northern Apennines. J Struct Geol 8:781–798

Kübler B (1967) La cristallinité de l'illite et les zones tout à fait supérieures du métamorphism. Etages Tectoniques, Colloque Neuchâtel. A La Bagonnière, Neuchâtel, Switzerland, pp 105–122

Limarino CO, Spalletti LA (2006) Paleogeography of the upper Paleozoic basins of southern South America: an overview. J South Am Earth Sci 22:134–155

Llambías EJ, Sato A, Ortiz Suárez A, Prozzi C (1998) In: Pankhurst RJ, Rapela CW (eds) The Proto-Andean Margin of Gondwana. Geological Society, London, Special Publications 142:325–341

López de Luchi MG, Cerredo ME, Siegesmund S, Steenken A, Wemmer K (2003) Provenance and tectonic setting of the protoliths of the metamorphic complexes of Sierra de San Luis. Revista de la Asociación Geológia Argentina 58:525–540

López de Luchi MG, Rapalini AE, Siegesmund S, Steenken A (2004) Application of magnetic fabrics to the emplacement and tectonic history of Devonian granitoids in Central Argentina. In: Martín-Hernández F, Luneburg C, Aubourg C Jackson M (eds) Magnetic fabric: methods and applications. Geological society, London, Special Publications 238:447–474

López de Luchi MG, Siegesmund S, Wemmer K, Steenken A, Naumann R (2007) Paleozoic tectonomagmatic evolution of the Sierra de San Luis (Sierras Pampeanas, Argentina). J South Am Earth Sci 24:138–166

Marheine D (1997) Zeitmarken im variszischen Kollisionsberreich des Rhenoherzynikums-Saxothuringikums zwischen Harz und sächsischem Granulitmassiv–Ergebnisse von K/Ar-Altersbestimmungen. Göttinger Arbeiten zur Geologie und Paläontologie 75:1–97

Martino RD (2003) Ductile deformation shear belts at Pampean Ranges near Córdoba. Revista de la Asociación Geológia Argentina 58:549–571

Martino RD, Steenken A, López de Luchi MG, Siegesmund S, Wemmer K (2005) Phyllites and meta-conglomerates of the San Luis Formation at Cañada Honda: kinematics and time constraints. Gondwana 12, Mendoza, Argentina. (Abstracts 247)

McDougall I, Harrison TM (1999) Geochronology and Thermochronology by the $^{40}Ar/^{39}Ar$ Method. Oxford University Press, New York Oxford

Mpodozis C, Kay S (1992) Late Paleozoic to Triassic evolution of the Gondwana margin: evidence from Chilenian Frontal Cordillera Batholiths (28°–31°S). Geol Soc of Am, Bullentin 104:999–1014

Nitsch KH (1970) Experimentelle Bestimmung der oberen Stabilitätsgrenze von Stilpnomelan. Fortschritte Mineralogie 47(1): 48–49

Ortiz Suárez AE, Casquet C (2005) Inversión metamórfica en el orógeno Famatiniano de la Sierra de San Luis, Argentina. Geogaceta 38:231–234

Ortíz Suárez AE, Prozzi CR, Llambías EJ (1992) Geología de la parte sur de la Sierra de San Luis y granitoides asociados, Argentina. Estudios Geológicos, 48, 269–277, (Madrid)

Pinotti LP, Tubía JM, D'Eramo FJ, Vegas N, Sato AM, Coniglio JE, Aranguren A (2006) Structural interplay between plutons during the construction of a batholith (Cerro Aspero batholith, Sierras de Córdoba, Argentina). J Struct Geol 28:834–849

Prozzi CR (1990) Consideraciones acerca del basamento de San Luis, Argentina. XI Congreso Geológico Argentino, San Juan, Actas 1:452–455

Prozzi CR, Ramos VA (1988) La Formación San Luis, paper presented at Primeras Jornadas de Trabajo de Sierras Pampeanas, Abstracts 1, Univ. Nac. San Luis, San Luis

Purdy JW, Jäger E (1976) K-Ar ages on rock forming minerals from the Central Alps. Memorie degli Istituti di Geologia e Mineralogia dell' Universita di Padova, vol 30, pp 1–31

Ramos VA (2001) The Southern Central Andes. In: Cordani U, Milani EJ, Thomaz Filho A, Campos DA (eds) Tectonic Evolution of South America, Rio de Janeiro, pp 561–604

Ramos VA, Basei MAS (1997) The basement of Chilenia: an exotic continental terrane to Gondwana during the early Paleozoic. In: Bradshaw JD, Weaver SD (eds) Terrane dynamics—97, International conference on terrane geology. Conference Abstracts 97:140–143, University of Canterbury, Christchurch

Ramos VA, Jordan TE, Allmendinger W, Mpodozis C, Kay SM, Cortés JM, Palma M (1986) Paleozoic terranes of the Central Argentine–Chilean Andes. Tectonics 5:855–880

Rapalini AE, Astini RA, Conti CM (1999) Paleomagnetic constraints on the tectonic evolution of Paleozoic suspect terranes from southern South America. In: Ramos VA, Keppie JD (eds) Laurentia–Gondwana Connections before Pangea. Geological Society of America, Special Papers 336:171–182

Rapela CW, Pankhurst RJ, Casquet C, Baldo E, Saavedra J, Galindo C, Fanning CM (1998) The Pampean Orogeny of the southern proto-Andes; Cambrian continental collision in the Sierras de Cordoba In: Rapela CW, Pankhurst RJ (eds) The proto-Andean margin of Gondwana. Geol Soc Spec Publ 142,181–217 (London)

Reuter A (1985) Korngrößenabhängigkeit von K-Ar Datierung und Illit-Kristalinität anchizonaler Metapelite und assoziierter Metatuffe aus dem östlichen Rheinischen Schiefergebirge. Göttinger Arbeiten zur Geologie und Paläontologie 27:1–91

Reuter A (1987) Implications of K-Ar ages of whole-rock and grain-size fractions of metapelites and intercalated metatuffs within an anchizonal terrane. Contrib Mineral Petrol 97:105–115

Reuter A, Dallmeyer RD (1989) K-Ar and ^{40}Ar/^{39}Ar dating of cleavage formed during very low-grade metamorphism: a review. In: Daly JS, Cliff RA, Yardley BWD (eds) Evolution of metamorphic Belts. Geological Society of London Special Publication. Blackwell, Oxford

Salfity JA, Gorustovich S (1983) Paleogeographía de la cuenca del Grupo Paganzo (Paleozoico Superior). Revista Asociación Geológica Argentina 38:437–453

Sato AM, González PD, Basei MAS (2005) Los ortogneises granodioríticos del complejo metamórfico Nogolí, Sierra de San Luis. 16th Congreso Geológico Argentino 1:41–48

Schumacher E (1975) Herstellung von 99.9997% ^{38}Ar für die ^{40}K/^{40}Ar Geochronologie. Geochronologia Chimia 24:441–442

Siegesmund S, Steenken A, López de Luchi MG, Wemmer K, Hoffmann A, Mosch S (2004) The Las Chacras-Potrerillos Batholith: structural evidences on its emplacement and timing of the intrusion. Int J Earth Sci 93:23–43

Sims JP, Ireland TR, Camacho A, Lyons P, Pieters PE, Skirrow RG, Stuart SPG, Miro R (1998) U-Pb, Th-Pb and Ar-Ar geochronology from the southern Sierras Pampeanas, Argentina; implications for the Palaeozoic tectonic evolution of the western Gondwana margin. In: Pankhurst RJ, Rapela, CW (eds) The proto-Andean margin of Gondwana. Geol Soc Spec Publ 142:259–281 (London)

Söllner F, de Brodtkorb MK, Miller H, Pezzutti NE, Fernández RR (2000) U-Pb zircon ages of metavolcanic rocks from the Sierra de San Luis. Argentina Rev Asoc Geol Argent 55:15–22

Sosa GM, Augsburger MS, Pedregosa JC (2002) Columbite-group minerals from rare-metal granitic pegmatites of the Sierra de San Luis, Argentina. Eur J Mineral 14:627–636

Steenken A, López de Luchi MG, Siegesmund S, Wemmer K, Pawlig S (2004) Crustal provenance and cooling of the basement complexes of the Sierra de San Luis: An insight into the tectonic history of the proto-Andean margin of Gondwana. Gondwana Res 7:1171–1195

Steenken A, Siegesmund S, López de Luchi MG, Wemmer K, Frei R (2006) The Famatinian and Achalian geodynamic evolution of the basement complex of the Sierra de San Luis: constraints from geochronological data and structural observations (Eastern Sierras Pampeanas, Argentina). J Geol Soc Lond 163:965–982

Steenken A, Siegesmund S, López Wemmer K, de Luchi MG (2008) Time constraints on the Famatinian and Achalian structural evolution of the basement of the Sierra de San Luis (Eastern Sierras Pampeanas, Argentina). J South Am Earth Sci 25:336–358

Steiger RH, Jäger E (1977) Subcommision on geochronology; Convention on the use of decay constants in geo- and cosmochronology. Earth and Planet Sci Lett 36:358–362

Stuart-Smith PG, Camacho A, Sims JP, Skirrow RG, Lyons P, Pieters PE, Black LP, Miro R (1999) Uranium-lead dating of felsic magmatic cycles in the southern Sierras Pampeanas, Argentina; implications for the tectonic development of the proto-Andean Gondwana margin. In: Ramos VA, Keppie JD (eds) Laurentia-Gondwana connections before Pangea Special Papers of the Geological Society of America 336:87–114

Thomas WA, Astini RA, Bayona G (2002) Ordovician collision of the Argentine Precordillera with Gondwana, independent of Laurentian Taconic orogeny. Tectonophysics 345:131–152

Toselli AJ (1990) Metamorfismo del Ciclo Pampeano. In: Aceñolaza FG, Miller H and Toselli AJ (eds) El Ciclo Pampeano en el Noroeste Argentino. Univ. Nac. Tucumán, Argentina. Serie Correlación Geológica 4:181–197

Varela R, Llambías EJ, Cingolani C, Sato AM (1994) Datación de algunos granitoides de la Sierra de San Luis (Argentina) e interpretación evolutiva. 7° Congreso Geológico Chileno, Concepción, Chile, Actas 2:1249–1253

Villa IM (1998) Isotopic closure. Terra Nova 10:42–47

von Gosen W (1998) The phyllite and micaschist group with associated intrusions in the Sierras de San Luis (Sierras Pampeanas/Argentina)—structural and metamorphic relations. J South AmEarth Sci 11:79–109

von Gosen W, Prozzi CR (1998) Structural evolution of the Sierra de San Luis (Eastern Sierras Pampeanas, Argentina): implications for the Proto-Andean margin of Gondwana. In: Pankhurst RJ, Rapela CW (eds) The Proto-Andean Margin of Gondwana. Geological Society, London, Special Publications 142:235–258

Weaver CE, Wampler JM (1970) K, Ar, illite burial. Geol Soc Am 81:2423–3430

Weber K (1972) Notes on the determination of illite crystallinity. Neues Jahrbuch für Mineralogie, Monatshefte 6:267–276

Wemmer K (1991) K/Ar-Altersdatierungsmöglichkeiten für retrograde Deformationsprozesse im spröden und duktilen Bereich—Beispiele aus der KTB-Vorbohrung (Oberpfalz) und dem Bereich der Insubrischen Linie (N-Italien)—Göttinger Arb Geol Paläont 51:1–61 (Göttingen)

Wemmer K, Ahrendt H (1997) Comparative K-Ar and Rb-Sr age determinations of retrograde processes on rocks from the KTB deep drilling project. Geologische Rundschau 86:272–285

Zhao MW, Ahrendt H, Wemmer K (1997) K–Ar systematics of illite/smectite in argillaceous rocks from the Ordos basin. China Chem Geol 136:153–169

Zhao B, Clauer N, Robb LJ, Zwingmann H, Toulkeridis T, Meyer FM (1999) K–Ar dating of white micas from the Ventersdorp Contact Reef of the Witwatersrand Basin, South Africa: timing of post-depositional alteration. Mineral Petrol 66:149–170

Zimmermann U (2005) Provenance studies of very low-to low-grade metasedimentary rocks of the Puncoviscana Formation in Northwest Argentina. In: Vaughan APM, Leat PT, Pankhurst RJ (eds) Terrane Processes at the Margins of Gondwana. Geological Society of London, Special Publications 246: 381–416