Involvement of the Argentine Precordillera terrane in the Famatinian mobile belt: U-Pb SHRIMP and metamorphic evidence from the Sierra de Pie de Palo

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ABSTRACT

New data suggest that the eastern margin of the Argentine Precordillera terrane comprises Grenvillian basement and a sedimentary cover derived from it that were together affected by Middle Ordovician deformation and metamorphism during accretion to the Gondwana margin. The basement first underwent low pressure/temperature (*P/T*) type metamorphism, reaching high-grade migmatitic conditions in places (686 ± 40 MPa, 790 ± 17 °C), comparable to the Grenvillian M_2 metamorphism of the supposed Laurentian counterpart of the terrane. The second metamorphism, recognized in the cover sequence, is of Famatinian age and took place under higher *P/T* conditions, following a clockwise *P-T* path (baric peak: 1300 ± 100 Mpa, 600 ± 50 °C). Low-U zircon overgrew detrital Grenvillian cores as pressure fell from its peak, and yields U-Pb SHRIMP ages of ca. 460 Ma. This is interpreted as the age of ductile thrusting coincident with early uplift; initial accretion to Gondwana must have occurred before this. The absence of late Neoproterozoic detrital zircons is consistent with a Laurentian origin of the Argentine Precordillera terrane.

Keywords: Argentina, Ordovician, continent collision, metamorphism, SHRIMP zircon dating.

INTRODUCTION

The origin of the Argentine Precordillera terrane has kept those involved in Paleozoic paleogeography and tectonics intrigued for some time. It is widely accepted as an exotic terrane, derived from Laurentia and accreted to the southwestern margin of Gondwana between Early Ordovician and Early Devonian time (Dalla Salda et al., 1992; Astini et al., 1995; Dalziel, 1997; Rapela et al., 1998). Another suggestion (Aceñolaza and Toselli, 1999) is that the terrane was autochthonous to Gondwana, originating in the Neoproterozoic margin of South America–Africa–Antarctica, and that it reached its present location by prolonged strike-slip movement. We provide new data highly relevant to these problems.

In the Precordillera, there is a nonmetamorphosed to weakly metamorphosed Cambrian-Devonian sedimentary cover (e.g., Keller et al., 1998) underlain by crystalline basement of Grenville age, inferred from U-Pb ages of xenoliths in Miocene intrusions (Kay et al., 1996). Grenvillian ages have also been obtained from the metamorphic rocks of the Sierra de Pie de Palo, Western Sierras Pampeanas, east of the Precordillera (Fig. 1), considered to be the main easternmost exposure of the Argentine Precordillera terrane basement. These rocks include a Neoproterozoic ophiolite sequence and orthogneisses (McDonough et al., 1993; Vujovich and Kay, 1998; Pankhurst and Rapela, 1998). Controls on the timing of the Paleozoic collision and tectonothermal history are sparse. A Middle Ordovician unconformity and change in style of sedimentation in the Precordillera are believed to indicate collision-related drowning of the former carbonate platform (Astini et al., 1995). Ramos et al. (1998) interpreted ^{39}Ar-^{40}Ar data from the Sierra de Pie de Palo as being consistent with recrystallization; a single amphibolite hornblende yielded a plateau age of 464.3 ± 0.3 Ma. However, the nature and extent of associated metamorphism are unknown, as are its pressure-temperature (*P-T*) characteristics and its relationship to plutonism and deformation in the Early Ordovician Famatinian mobile belt of the Sierras Pampeanas (Pankhurst and Rapela, 1998).

Our U-Pb SHRIMP data and metamorphic evidence demonstrate that the easternmost exposures of the Argentine Precordillera terrane were involved in Famatinian orogenic events and underwent relatively high *P/T* type regional metamorphism. A metamorphosed sedimentary cover to the Grenvillian basement is recognized for the first time, consistent with a Laurentian origin. The time of initial terrane collision and prograde Famatinian metamorphism is defined as slightly before 460 Ma.

GEOLOGY OF SIERRA DE PIE DE PALO

The Sierra is an imbricate ductile thrust system with a top-to-the-west sense of relative movement. We distinguish a number of allochthonous tectonic units overlying epimetamorphic basement formed by the Caucete Group sedimentary rocks (Fig. 1). The lower unit consists of mafic and ultramafic rocks (for which a Grenvillian ophiolite origin was suggested by Vujovich and Kay, 1998), black schists, and quartzites. It is separated from the Caucete Group by the Pirquitas thrust, which underwent protracted activity from 464 Ma until ca. 396 Ma (Ramos et al., 1998). The upper units comprise monotonous migmatites, schists, and quartzites, topped by the Difunta Correa Sedimentary Sequence of marbles, Ca-pelitic schists, and quartzites (Baldo et al., 1998). Amphibolites are widespread, particularly in the lower unit and Difunta Correa Sedimentary Sequence; most were probably dikes, although some are metasediments. Peraluminous and metaluminous orthogneisses are also common, as are mylonites, particularly at the main unit boundaries. At least two foliations are found in zones protected from ductile shearing; the second is usually a differentiated crenulation cleavage. Retrograde extensional shear zones, with a top-to-the-east sense of relative movement, are present in the eastern part of the Sierra. They are superimposed on the thrust zones and caused major thinning of the sedimentary sequence in the uppermost tectonic units. The thickness of the tectonic pile is at least 15 km.

U-Pb SHRIMP GEOCHRONOLOGY

Sample SPP-1001 is a mylonitic Ca-pelitic schist from north of the mapped area (on the road to the top of the Sierra; 31°23′30″S, 68°01′07″W). Its mineral composition corresponds to similar rocks in the Difunta Correa

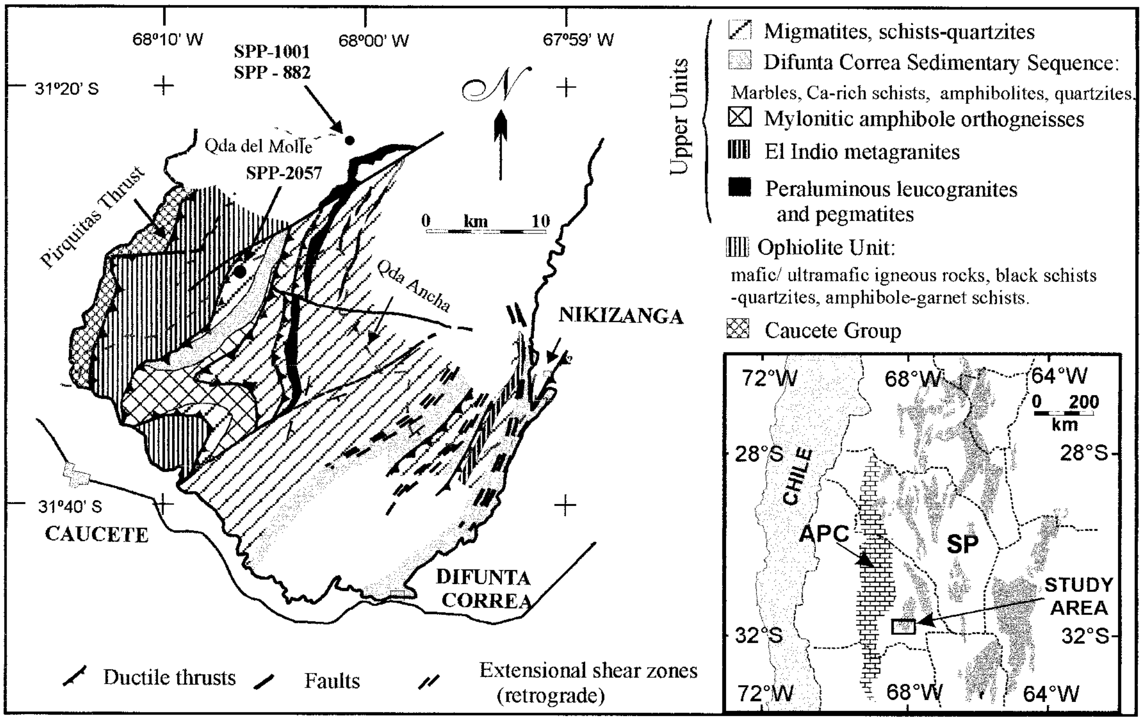

Figure 1. Geological sketch map of southern Sierra de Pie de Palo. Inset shows location of Sierras Pampeanas (SP) and Argentine Precordillera (APC).

Sedimentary Sequence: Qtz, Pl, Ms, Bt, Grt, Hbl, Ep, Ilm, Rt, and Zr (mineral abbreviations after Kretz, 1983). The separated zircons are subhedral and elongate, to 200 μm. Cathodoluminescence imaging shows their composite nature; cores consisting of fragments and subrounded grains with oscillatory zoning characteristic of igneous crystallization are invariably overgrown by unzoned low-U rims, generally 10–60 μm thick (Fig. 2). Discrete cores and rims were selected for ion microprobe U-Pb analysis on SHRIMP II at the Australian National University, using a beam with an ~25-μm-diameter spot (Compston et al., 1992). Data for 10 cores and 10 rims are plotted in Figure 2 (see Data Repository[1]). The cores have inferred crystallization ages of 1032–1224 Ma (apart from one with an age of ca. 2900 Ma). With a single exception, the rims have Th/U = 0.01–0.1, indicating a metamorphic origin, and plot close to 460 Ma; this is interpreted as the age of metamorphic overgrowth. Two rim analyses plot to the right of the main group and are thought to reflect subsequent Pb loss.

CONDITIONS OF METAMORPHISM

The *P-T* conditions of metamorphism were assessed from Grt microdomains using the computer program TWQ2.02 and the thermodynamic database BA96a.DAT (Berman, 1991). Two contrasting rocks are compared: a mylonitized Ca-pelitic schist (SPP-882) collected a few meters from sample SPP-1001, and a mylonitized migmatitic paragneiss (SPP-2057) from the bottom of one of the upper units (Fig. 1).

SPP-882 has a complex mineralogy (Qtz, Ms, Pg, Bt, Grt, Ky, St, Pl, Hbl, Ep, Rt, Ilm) with evidence of three superimposed foliations (Baldo et al., 1998). Garnet, Ms, Bt, Ky, St, Hbl, and Rt are prekinematic relative to the mylonitic foliation, S_{myl}, which is defined by a banded matrix of granoblastic Qtz lenses, layers of Pl, Ep, and dynamically recrystallized Ms, Pg, and Bt. Garnet porphyroclasts enveloped by S_{myl} contain orientated inclusions that define a discordant sigmoidal internal S_1 foliation. This suggests that Grt grew in microlithons during the development of a new external foliation (S_2) that was obliterated by mylonitization, except in strain shadows where relics of deformed S_1 are preserved. A differentiated crenulation cleavage is common in these rocks away from the shear zones. Minerals contained in garnet are Qtz, St, Mrg, Bt, Pg, Ep, Chl, Rt, Ilm, and Pl. Garnet shows

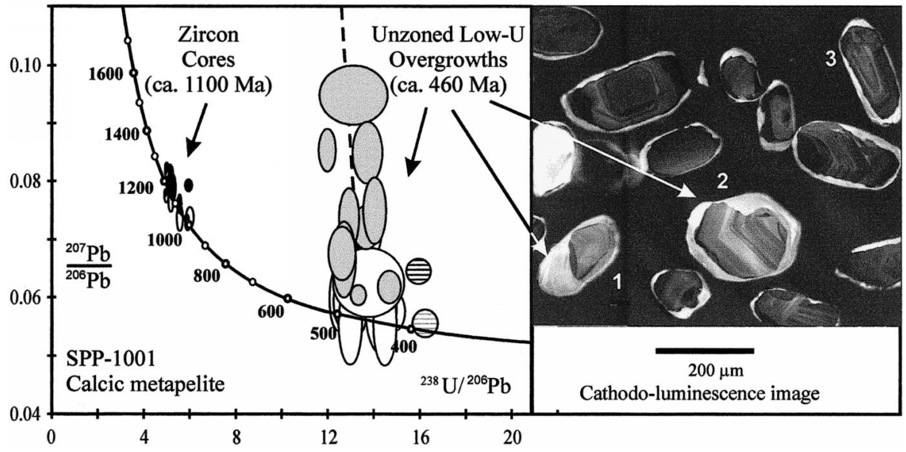

Figure 2. Tera-Wasserburg U-Pb concordia plot for SHRIMP spot analyses of zircons from sample SPP-1001. Black ellipses are 68% confidence limits for analyses of crystal cores, uncorrected for common Pb; shaded ellipses are for low-U overgrowths (see cathodoluminescence image). Open ellipses show points shifted to concordia when corrected for common Pb, as estimated from measured ^{204}Pb peaks, albeit with error magnification due to low Pb contents. Data for cores clearly indicate crystallization in interval 1000–1200 Ma, whereas rims formed at close to 460 Ma (excluding single cross-hachured ellipse, which seems to have undergone more recent Pb loss). There is no evidence for any event between these two ages.

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[1] GSA Data Repository item 2001084, U-Pb SHRIMP data for sample SPP-1001, and chemical analyses of minerals considered for *P-T* computations, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2001.htm.

growth zoning with a continuous increase of X_{grs} (X = mole fraction) and X_{prp} relative to X_{alm} and X_{sps} toward the rim. Three *P-T* points were determined in this rock (Fig. 3). M_1 (650 ± 50 Mpa, 550 ± 50 °C) corresponds to conditions during prograde growth, computed from core garnet and mineral inclusions. M_2 (1300 ± 100 Mpa, 600 ± 50 °C) corresponds to close to peak pressure conditions, computed from rim garnet and minerals protected from S_{myl} in a nearby strain shadow. M_3 (900 ± 130 Mpa, 570 ± 5 °C) represents mylonitization and is based on syntectonic matrix minerals.

SPP-2057 shows a penetrative mylonitic fabric that wraps around pretectonic Grt (type II), Pl, Ms, By, fibrolitic pseudomorphs after Ky blades, and Ilm. Sillimanite is also found included in Ms, defining an internal foliation discordant to S_{myl}. Scarce relicts of St (and Bt and type I Grt) are preserved armored in plagioclase porphyroclasts. Mylonitization was accompanied by dynamic recrystallization of micas along grain boundaries and of Qtz as ribbons; Rt formed at the expense of Ilm. Clusters of crystallites of an Al silicate (probably Ky) also formed during shearing, along grain boundaries of Pl, Grt, and mica, with a mean trend parallel to S_{myl}. Furthermore, there are very small (~0.1 mm) idiomorphic Grt grains that apparently grew across S_{myl} (type III, Fig. 4). These probably formed late during shearing and are chemically unlike the pretectonic garnets. Type I Grt is the poorest in Ca ($alm_{79.2}prp_{15.2}grs_{3.7}sps_{1.65}$). Type II Grt porphyroclasts are relatively homogeneous and slightly richer in Ca ($alm_{78-79.3}prp_{13-14.4}grs_{4.9-6}sps_{1.2-2.7}$), except at the edges, where an abrupt jump to type III compositions is found. Type III Grt is Ca rich and Mn poor and displays a strong zonation: increasing X_{Ca} and decreasing X_{Mg}, X_{Fe}, and X_{Mn} toward the rim, where grossular content can be as high as 20 mol% (Fig. 4). Both pretectonic and recrystallized biotites are homogeneous, with Mg/(Fe + Mg) ratios of 0.54–0.48 and Ti contents of 0.32–0.38 atoms per formula unit (afu). However, relict Bt armored in Pl is richer in Ti (0.49 afu) and Mg (Mg/[Fe+Mg] = 0.6). Plagioclase shows normal zoning, from Ab_{70} (cores) to Ab_{77} (rims). Two *P-T* points were determined (Fig. 3), one for the migmatitic stage (686 ± 40 Mpa, 790 ± 17 °C) and one for the stage of type III garnet growth (1140 ± 135 Mpa, 615 ± 70 °C). In the first case Sil, core Pl, and Ilm along with Bt and Grt armored in Pl, and Kfs (completely retrogressed to Ms) were considered; in the second, Ky, rim Pl, Ms, Bt, Rt, and rim type III Grt were used (see footnote 1).

DISCUSSION

The Ca-metapelite contains detrital zircon derived by erosion of Grenvillian basement and thus represents a sedimentary cover se-

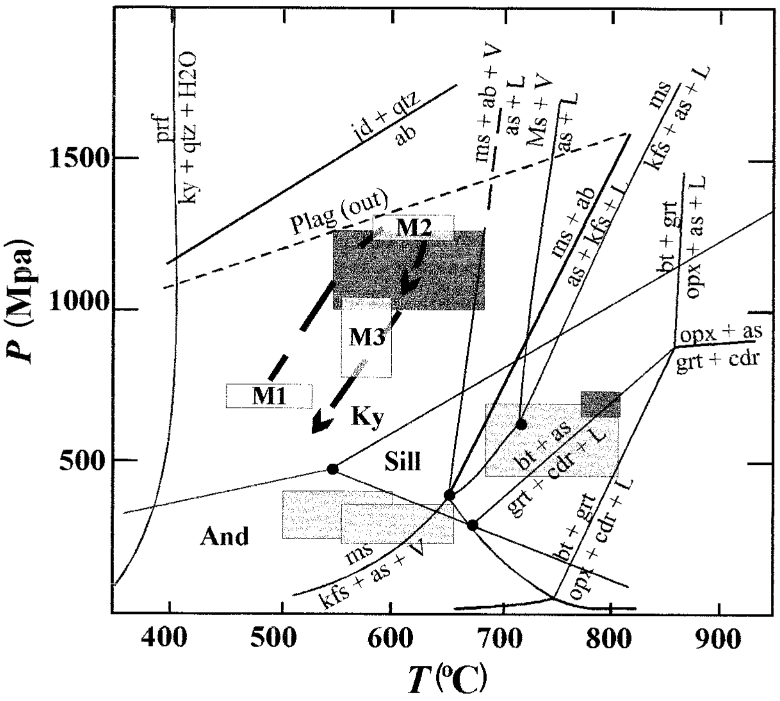

Figure 3. Pressure-temperature (*P-T*) plot of metamorphic conditions derived from samples from Sierra de Pie de Palo. White boxes: mylonitic Ca-pelitic schist SPP-882 (Baldo et al., 1998). Dark gray boxes: mylonitic migmatite SPP-2057. Light gray boxes: *P-T* conditions for Grenvillian M2 metamorphism in Llano uplift, Texas (Carlson and Schwarze, 1997). Arrows: *P-T* trajectories. Equilibrium curves are from Spear et al. (1999) and Spear (1993). Abbreviations after Kretz (1983).

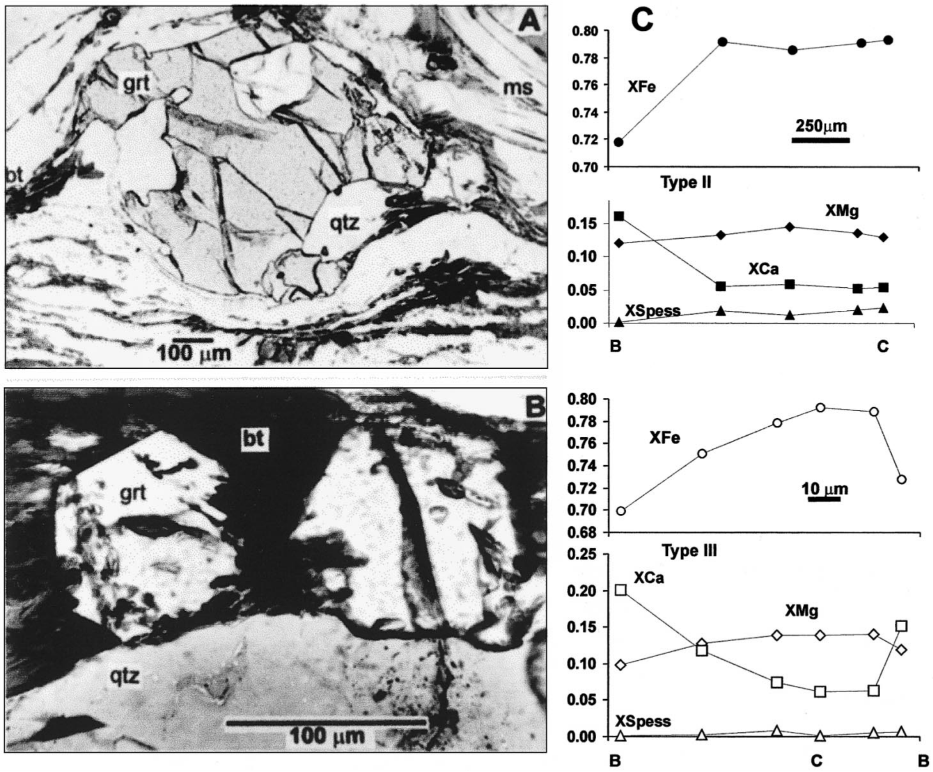

Figure 4. Photomicrographs of mylonitized migmatite SPP-2057, showing (A) pre-mylonitic type II garnet and, (B) late mylonitic idiomorphic type III garnet. Respective chemical zoning is shown on right (C) (C is core; B is border). Abbreviations after Kretz (1983).

quence to the basement of the Argentine Precordillera terrane. This cover could be equivalent to the lower part of the Precordillera sedimentary sequence or much older, i.e., Neoproterozoic. The absence of derived zircons between ca. 1100 Ma and 460 Ma shows that it underwent no significant tectonothermal event until the Middle Ordovician. This age gap is a characteristic of the Grenville province of Laurentia: in Gondwana (including the Eastern Sierras Pampeanas) a succession of Neoproterozoic events is recorded in zircon inheritance patterns (Ireland et al., 1994; Sims et al., 1998; Pankhurst et al., 2001). Evidence for true Grenvillian basement in the Sierra de Pie de Palo includes conventional U-Pb zircon data from metabasites of the lower ophiolitic unit (McDonough et al., 1993) and a Rb-Sr isochron age for orthogneiss of unknown structural position (Pankhurst and Rapela, 1998). Thus an unconformity must exist, masked by Famatinian deformation.

Because no pre-Ordovician metamorphism is registered in the zircons of sample SPP-1001, and the three *P-T* points determined in the equivalent sample SPP-882 suggest a single clockwise *P-T* path, we infer that this path results from Famatinian metamorphism alone. Metamorphic conditions are estimated as between high *P-T* type (no blueschists or eclogites of Famatinian age have been found in the sequence) and medium *P-T* (Barrovian) type. We envisage that peak pressure conditions in these rocks fell during postcollisional uplift on the mylonitic shear zones (proshears). In contrast, migmatite SPP-2057 shows two contrasting metamorphic histories: an older event under relatively low *P-T* type conditions, and a younger (synmylonitic) event comparable to the close to peak conditions of sample SPP-882. The first might equate to the Grenvillian M_2 metamorphism in the Llano uplift area of Texas (Carlson and Schwarze, 1997; Mosher, 1998), which is considered to be the Laurentian counterpart of the Argentine Precordillera terrane (e.g., Dickerson and Keller, 1998). Thus we envisage that the migmatitic gneisses and the equivalent schist-quartzite sequence, together with some orthogneisses, represent the true Grenvillian basement.

Zircon overgrowths indicate metamorphic reactions involving the release of Zr from minerals such as amphibole and garnet (Fraser et al., 1997). Both minerals occur in the premylonitic assemblage of SPP-1001, but were consumed during mylonitization. Thus we suggest that 460 Ma is the age of ductile thrusting in the Sierra de Pie de Palo. Because pressure had by then dropped from its peak (Fig. 3), this must be taken as a minimum for the age of underthrusting of the Argentine Precordillera terrane beneath post-Cambrian Gondwana, i.e., the initiation of collision. Premylonitic foliations and prograde metamorphism shown by the Difunta Correa Sedimentary Sequence probably developed earlier during underthrusting, consistent with an early Middle Ordovician age for the drowning of the Precordillera carbonate platform (Astini et al., 1995).

The Sierra de Pie de Palo thus represents part of the eastern margin of the Argentine Precordillera terrane that was thoroughly involved in the tectonothermal activity of the Famatinian mobile belt. Because this part of the belt was thrust westward along the Pirquitas thrust, the Precordillera does not show the effects of Famatinian events to any significant extent. Our results support a Laurentian origin of the Argentine Precordillera terrane and Early to Middle Ordovician collision with Gondwana.

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