STRUCTURE, METAMORPHISM AND AGE OF THE PAMPEAN-FAMATINIAN OROGENIES IN THE WESTERN SIERRA DE SAN LUIS

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INTRODUCTION

The Eastern Sierras Pampeanas basement is located in the central region of Argentina, and includes several metamorphic and igneous complexes distributed within two main ranges, the Sierras de Córdoba and Sierras de Chepes-Ulapes-San Luis. The basement in the Sierras de Córdoba consists of a well-preserved sequence of structural, metamorphic and magmatic events (Martino et al., 1995), developed during the Early to Mid-Cambrian Pampean orogeny (Rapela et al., 1998). Subsequent emplacement of Ordovician granitoids and wrench tectonics were interpreted as inner cordilleran counterparts of the Famatinian magmatic arc (Rapela et al., 1998), developed to the west along the Sierras de Chepes-Ulapes-San Luis (Llambías et al., 1998; Pankhurst et al., 1998). Here, the basement was strongly overprinted not only by the emplacement of the Famatinian magmatic arc, but also by the coeval Early Ordovician-Devonian structural and metamorphic events.

The basement in the Sierra de San Luis consists of a sequence of structural and metamorphic events attributed to Pampean and Famatinian Cycles (Criado Roqué et al. 1981). The sequence of Pampean events (Late Precambrian-Early Cambrian) differs from that of Sierras de Córdoba because, it is only preserved as small remnants with NW-SE trending structures (Criado Roqué et al. 1981; González and Llambías, 1998; von Gosen and Prozzi, 1998). These remnants are less affected by the later penetrative NNE-SSW trending structures attributed to the Famatinian events -Late Cambrian to Devonian (González and Llambías, 1998; von Gosen and Prozzi, 1998).

Unraveling the sequence of structural and metamorphic events and the geochronology of the basement of the Sierra de San Luis has been our two main objectives. Detailed studies were carried out in the southwestern region of the Sierra (32°49'-33°02'S / 66°07'-66°20'W; Fig. 1A) and their results are presented in this paper. We recognized a clear separation between two sequences of events: 1) the pre-Famatinian and 2) Famatinian metamorphism, deformation and magmatism. The pre-Famatinian sequence of events shows a prograde high temperature-low pressure Buchan type metamorphism, whereas the Famatinian sequence of events defines a retrograde counterpart, with a medium temperature-medium pressure Barrovian type metamorphism. Both sequences of events are linked through in a counterclockwise P-T-time path. Although most of the isotopic ages of the pre-Famatinian events were reset during the Famatinian orogeny, we could obtain some relict Early to Late Cambrian ages on gneisses and amphibolites. We ascribed them to the Pampean orogeny and also constrained the isotopic ages of the subsequent Early Ordovician to Devonian sequence of overprinting events related to the Famatinian orogeny.

GEOLOGICAL SETTING AND ANALYSIS OF P-T-t PATHS

The metamorphic basement of the southwestern Sierra de San Luis (Fig. 1A) is composed of: 1) A supracrustal association (metapelites, metaquartzites and mafic-

ultramafic metavolcanic rocks with minor banded iron formations, marbles and calcsilicates) and 2) Gneisses, migmatites and amphibolites.

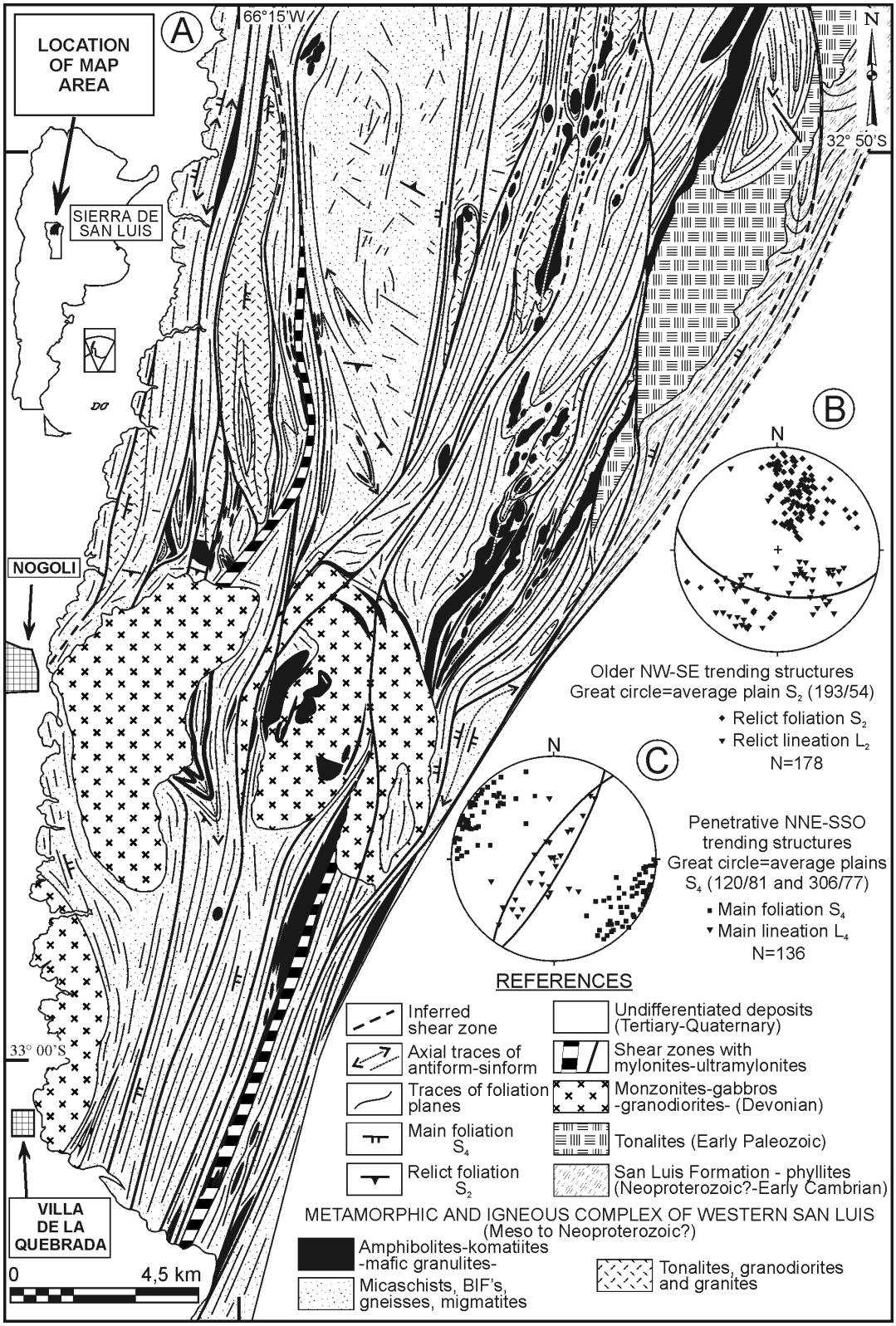

Figure 1: A: Simplified geological map of the western San Luis basement based on our own investigations. B and C: Equal area, lower hemisphere stereoplots of fabric elements within the metamorphic complex, with indication of the main average foliation planes.

The deposition of the original volcanic-sedimentary sequence and its structural and metamorphic evolution took place since pre-Famatinian times and continued through the Early Paleozoic Famatinian events (González and Llambías, 1998; von Gosen and Prozzi, 1998). The possibility of a crystallization age as old as ~1,5 Ga for the mafic to ultramafic rocks, was pointed out by Sato et al. (2001) based on one Sm-Nd whole rock isochron.

The structural analyses revealed two sets of structural orientations in the metamorphic rocks: 1) Remnant NW-SE trending structures (S_0 to S_3) attributed to pre-Famatinian events. These older foliations are preserved in the cores of the amphibolite bodies or along discrete belts of schists and gneisses. 2) Penetrative NNE-SSW trending structures (S_4) ascribed to the Famatinian events. These analyses were accompanied by detailed metamorphic studies (textural and mineral composition-unpublished EPMA data). The reconstruction of P-T trajectories was enabled on the basis of the integration of all these informations.

REMNANT PAMPEAN NW-SE TRENDING STRUCTURES

Tese are characterized by relics of S_0 (pelite-psamite banding in schists and gneisses) affected by subsequent D_1-D_2-D_3 deformations leading to the development of F_1 isoclinal, F_2 tight and F_3 open folds. F_1 and F_2 folds are related to S_1 axial plane cleavage and S_2 foliation respectively, whereas S_3 mylonitic foliation is associated to narrow shear zones developed parallel to S_2-F_2 axial planes. The S_2 defines the relics of the older NW-SE trending foliation (Fig. 1B). The parallelism between S_1 and S_2 suggest a co-axial D_1-D_2 compressive deformation coeval with prograde metamorphism (up to high greenschist-low amphibolite facies). Large tonalitic to granitic pre-Famatinian plutons and several small bodies (Fig. 1A) intruded the metamorphic complex following the previous S_0-S_2 planar fabric and during the coeval -or later to- S_3 development. The heat and fluid transfer from granitoid emplacement to the country rocks increased the regional geotherms. The thermal input on the pelitic protoliths lead to the growth of small grains of cordierite and ~10 cm long andalusite prism on biotite-muscovite aggregates followed by sillimanite replacement, whereas the heat and fluid transfer lead to the partial melting of the schists and gneisses. The thermal input on the mafic-ultramafic rocks also increased the metamorphic grade, from amphibolite facies (Ca-clinoamphibole + plagioclase + magnetite or orthoamphibole + Fe-Mg-clinoamphibole + plagioclase) to locally granulite facies (garnet + cpx or opx+hercynitic spinel+olivine). The last paragenesis partially obliterated the previous nematoblastic arrangement with poligonal granoblastic textures.

The thermally metamorphosed country rocks containing both aluminosilicates + cordierite in metapelites and the orthoamphibole + Fe-Mg-clinoamphibole or opx + hercynitic spinel + olivine in mafic-ultramafic rocks, suggests a typical paragenesis of low pressure-high temperature metamorphism (Buchan type). Structure, mineral paragenesis and metamorphism data led us to the interpretation of a near isobaric heating trajectory, for the pre-Famatinian sequence of events (Fig. 2). A small loop of retrogression with cooling and hydration after the thermal peak is supported by rims of a second generation of Ca-clinoamphibole surrounding the granulite paragenesis and by the development of veinlets filled with talc + calcite + chlorite.

PENETRATIVE FAMATINIAN NNE-SSW TRENDING STRUCTURES

After the development of the older NW-SE trending structures, the fabric within the metamorphic complex experienced a new D_4 deformation. Within the schistose mesosomes of the partial melted metapelites, after S_1-S_3 and prior to syn-S_4 development, garnet idioblasts (<0,5cm) grew followed by prismatic staurolite (~0,3cm). This new minerals overprinted the low P-high T paragenesis and led us to the interpretation that D_4 is the result of a period of compression, if we assume that the garnet grew during the peak pressure. This increment of P needs a subsequent tectonic loading and this is related to the onset of complex N-S to NNE-SSW trending, east or west steeply to subvertical dipping shear zones, developed and reactivated through several times with thrust sheets and mylonitic foliation (Fig.1A and 2). This event represents an important switching of compressive stress orientation associated to medium P and medium T metamorphism (Barrovian type). The near-orthogonal NNE-SSW trending S_4 is the most penetrative foliation in the metamorphic

complex (Fig.1C), which is recorded as a reactivation of older S_1-S_3 during D_4. The peak P was followed by the beginning of the basement exhumation (through multiple reactivated early shear zones) under near isobaric cooling trajectory, which defines the Famatinian sequence of events (Fig. 2). This is supported by the overprinted pos-tectonic Mg-chloritoid idioblast through the entire S_4 (in metapelites) and by the retrogressed pre-Famatinian amphibolite-granulite facies assemblages up to greenschist facies, leading to the formation of tremolite-actinolite-talc-chlorite paragenesis (in mafic-ultramafic rocks).

The integration of both sequences of events (pre-Famatinian and Famatinian) defines a counterclockwise P-T-time evolution path for the western Sierra de San Luis.

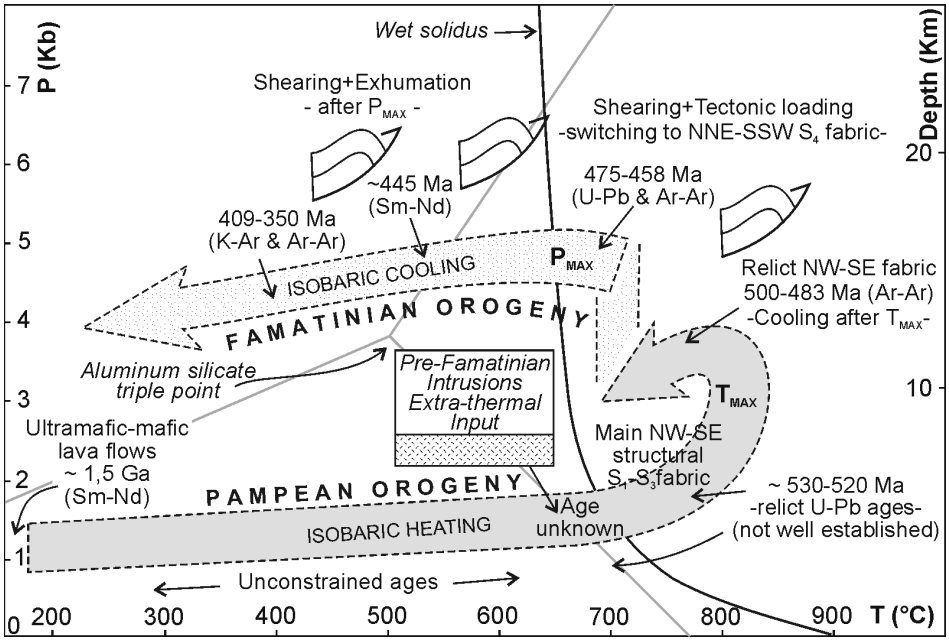

Figure 2: Simplified counterclockwise P-T-time path diagram with broadly estimated conditions for the evolution of the metamorphic complex of western Sierra de San Luis, based on structural, petrographic and geochronological studies. The gray arrow shows the reconstructed trajectory for the Pampean events, whereas the doted arrow the trajectory for the Famatinian evolution.

GEOCHRONOLOGICAL CONSTRAINT AND DISCUSSION

Various isotopic methods were applied to constrain the timing of the sequence of metamorphism-deformation events as discussed above. A gneiss composed of quartz, plagioclase, micas, sillimanite, garnet and minor zircon - monazite and collected from the interior of a belt with remnant NW-SE trending structures (strongly affected in the borders by a penetrative NNE-SSW trending S_4), was analyzed by U-Pb method. Four populations of monazite crystals have been separated for conventional U-Pb dating in the Laboratories of the CPGeo (Instituto de Geociencias, Universidade de São Paulo, Brazil). Three populations define an age of 458,2 ± 2,7 Ma (2σ), with MSWD 0,26.

The conventional U-Pb method was complemented with electron microprobe dating. Chemical Th-U-total Pb dating with the electron microprobe was also performed for the same gneiss sample at the Microprobe Laboratory of the same institute, following analytical procedures and data treatment described by Vlach and Gualda (2000). Up to 25 analytical points over 4 selected monazite grains (the larger isolated ones) were analyzed. The weighted average age obtained is 470 ± 15 Ma. Within errors this age agrees with the conventional analysis and we interpret it as the Early to Mid-Ordovician (time-scale of Gradstein and Ogg, 1996) D_4 event related to the peak P and the formation of penetrative NNE-SSW trending structures (Fig. 2).

The ages obtained over five (cores and rims) of the 25 analytical points range between 520 and 490 Ma, with errors in the order of 30 and 50 Ma (2σ). Although these older Early

Cambrian-Tremadoc ages comes from few points and should be considered with caution, they may represent some relict Pampean stage of metamorphism-deformation related to D_2-D_3. In accordance with this interpretation von Gosen and Prozzi (1998) summarized for the central part of the Sierra de San Luis, a structural fabric comparable to the D_1-D_3 of the western region. Over the same area, Sims et al. (1998) analyzed zircon cores and rims (U-Pb SHRIMP) of one garnet-sillimanite gneiss (comparable with our sample), obtaining Neoproterozoic to Early Cambrian peak at ~530 Ma for the cores, and a weighted age of 459 ± 5 Ma for the overgrown rims. Although there are not conclusive Neoproterozoic-Early Cambrian ages of metamorphism-deformation related to D_2-D_3, we can not exclude certain Pampean component in the NW-SE fabric.

Several Mg-hornblende grains collected from two amphibolites with relict NW-SE trending S_2 were irradiated in step heating Ar-Ar analyses, carried out at Radiogenic Isotopes Laboratory (Department of Geological Sciences, Ohio State University). The plateau ages obtained range between 475,8 ± 2,5 and 457,1 ± 3,0 Ma. These Early to Mid-Ordovician data are consistent with the ages obtained with both U-Pb methodologies for D_4-related events. The integrated total-gas Ar-Ar ages (derived from the summation of all fractions of the incremental-heating analysis) range between 500 and 483 Ma. These Late Cambrian to Arenig ages partly overlap the old 520-490 Ma interval, suggesting the same relict Pampean ages related to D_2-D_3 events. If the peak of Pampean events was at ~530-520 Ma, then we can interpret the 500-483 Ma as two possibilities: 1) a cooling Pampean age (~ the loop in Fig. 2), developed after peak T (post-D_2 / pre to sin-D_3), and prior to peak P related to D_4. 2) The earliest stages of compressive D_4 Famatinian deformation.

Sm-Nd whole rock + plag-amph-garnet isochron performed over an amphibolite with NNE-SSW trending S_4, yielded an age of 445 ± 21 Ma with initial $^{143}Nd/^{144}Nd$ 0,511850±0,000028 and MSWD 2,2. This Late Ordovician Sm-Nd age probably represents some shear zone metamorphism (post peak P of ~475-458 Ma) related to retrogression during early stages of the isobaric cooling trajectory (Fig. 2). As evidence of the continuous shearing developed in post-Ordovician times, Sims et al. (1998) and Sato et al. (1999) reported shear zone metamorphism and resetting ages ranging between 409 and 350 Ma. These Devonian ages were related to localized shear zones affecting the whole metamorphic complex.

The structural and metamorphic evolution of the possible Early Mesoproterozoic (*c*.1,5 Ga) volcanic-sedimentary sequence took place since pre-Famatinian time and continued through the Early Paleozoic Famatinian events. The timing of the Pampean events in the Sierras de Córdoba is well constrained with geochronological data. On the contrary, the Pampean events in the Sierra de San Luis are poorly constrained. Although the relict Early Cambrian ages of ~530-520 Ma are not statistically sufficient to ascribe the peak of the pre-Famatinian orogeny, we can not exclude certain "Pampean" component in the old NW-SE fabric. At this stage we can not also exclude possible ages of metamorphism-deformation, after 1,5 Ga and before 530 Ma. The time interval 500 to 483 Ma probably represents the cooling of Pampean events, and it seems to be the linkage to the subsequent (concomitant?) earliest stages of Famatinian compression. This also suggests not only a gradual change between Pampean and Famatinian events in the Sierra de San Luis, but also the absence of an abrupt discordance between both orogenies.

The switch of the structural trend from Pampean NW-SE to Famatinian NNE-SSO is a dynamic process of shortening by thrust loading. This switching probably begun around 483 Ma and continued within the time interval 475 to 458 Ma, as a consequence of some changes in plate convergence rates by docking of some continental block. From a more regional point of view this switching is related to the Laurentian-derived exotic terrane docked to the southwestern margin of Gondwana during Famatinian Orogeny. On the basis of our structural, metamorphic and isotopic data we interpret that the beginning of the docking and final amalgamation of the Laurentian-derived terrane took place during Early to Mid-Ordovician times, prior to the Late Ordovician "Ocloyic orogenic phase" deformation (~450 Ma) as previously suggested.

In summary, the global analysis of the structure, metamorphism and age defines a counterclockwise P-T-time path with two individual and distinctive trajectories of metamorphism-deformation in the rocks: 1) Prograde isobaric heating (high T-low P Buchan type) associated to large granitoid intrusion at pressures below aluminum silicate triple point and within amphibolite facies, which we assigned to the Pampean orogeny. 2) Retrograde counterpart with isobaric cooling (medium T-medium P Barrovian type) after a period of compression by tectonic loading, belonging to the Famatinian orogeny.

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