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The origin and petrologic evolution of the Ordovician Famatinian-Puna arc

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ABSTRACT

Elemental chemistry, radiogenic isotopic data, and zircon U-Pb inheritance patterns for the Famatinian-Puna arc suggest that the primary petrogenetic process operating in the arc was mixing between subarc mantle-derived gabbroic magmas and metasedimentary materials without a substantial component of lower-crustal continental basement rocks. This mixing is observable in the field and evident in variations of chemical elemental parameters and isotopic ratios, revealing that hybridization coupled with fractionation of magmas took place in the upper 25 km of the crust. Intermediate and silicic plutonic rocks of the Famatinia-Puna arc formed in a subduction setting where the thermal and material input of mantle-derived magmas promoted fusion of fertile metasedimentary rocks and favored mixing of gabbroic and dioritic magmas with crustal granitic melts. Whole-rock geochemical and isotopic data for the Famatinian-Puna magmatic belt as a whole demonstrate that the petrologic model studied in detail in the Sierra Valle Fértil–La Huerta section has the potential to explain generation of plutonic and volcanic rocks across the Early Ordovician western Gondwanan proto-Pacific margin. This example further underscores the significance of passive-margin sedimentary accumulations in generating continental arcs.

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INTRODUCTION

Interest in subduction-related magmatic belts centers on their importance to the study of: (1) the generation of continental-scale intermediate magmatism, (2) the causal mechanism of volcanic hazards and major earthquakes, (3) the nature of hydrothermal ore systems, and (4) the evolution and growth of the continental crust (Gill, 1981; Tatsumi and Eggins, 1995; Ducea and Barton, 2007). Ancient magmatic belts from destructive plate margins are dominated by Cordilleran-style intermediate and silicic plutonic rocks. The extent to which the dominant intermediate and silicic plutonic rocks from destructive plate margins reflect either addition of new material to the crust, recycling of preexisting crust, or a mixture between the two has been strongly debated (for a recent discussion, see Brown, 2013). The issue is central for deciphering the chemical evolution and net growth rate of the continental crust (Davidson and Arculus, 2006; Kemp et al., 2009; Cawood et al., 2012).

This study reviews isotopic data from one of Earth's largest magmatic arcs, the Ordovician Famatinian-Puna arc from NW Argentina and Bolivia. Our initial focus was the deepest known crustal section of the arc, which makes up the Sierra Valle Fértil–La Huerta, one of the Sierras Pampeanas (Fig. 1). The petrogenesis of Early Ordovician plutonism from Valle Fértil and La Huerta was deciphered through the combined study of petrography, whole-rock geochemistry, and radiogenic isotopes and U-Pb zircon geochronology (Otamendi et al., 2009a, 2012; Ducea et al., 2010). Subsequently, we extended our focus to various exposures of the Famatinian arc located to the north into the Puna Plateau. Preliminary observations from there, as well as previously published data, are used to interpret the petrogenetic and tectonic evolution of the arc. The principal conclusions drawn here are that the arc was active and in flare-up mode for a relatively short period of time, and it formed via a combination of subcraton (isotopically "enriched") mantle-derived magmas and melts derived from a thick and melt-fertile suite of passive-margin sedimentary rocks, regionally known as the Puncoviscana Formation and regionally correlative units. There is no evidence for the existence of a cratonal lower crust under the Famatinian arc.

GEOLOGICAL SETTING

Summary of the Geologic Evolution of the Late Neoproterozoic to Ordovician Western Gondwana Margin

The proto-Andean margin of western Gondwana has experienced fairly continuous subduction with relatively short interruptions during terrane accretions (Cawood, 2005) or periods when the margin was a transform fault since the latest Proterozoic–early Paleozoic. The Pampean magmatic arc was built on the once-passive margin of a western Gondwanan landmass when subduction began at ca. 550 Ma (Rapela et al., 1998; Schwartz et al., 2008). Subduction-related magmatic activity paused between ca. 515 and 495 Ma, stepped out to the west, and resumed on the western margin during the growth and evolution of the Famatinian magmatic arc (Pankhurst et al., 1998). The lack of subduction-related arc magmatism during the Late Cambrian was speculatively interpreted to have been caused by either accretion of the Pampean terrane to the proto-Pacific Gondwanan margin (Rapela et al., 1998) or a ridge-trench collision on the border of the Gondwanan landmasses (Schwartz et al., 2008). Current understanding shows that the Pampean thermo-tectonic orogeny was short-lived (ca. 530–515 Ma) and affected thick Neoproterozoic–Early Cambrian sedimentary sequences (Martino et al., 2009; Drobe et al., 2009). These thick, mostly marine sedimentary sequences, which are regionally referred to as the Puncoviscana Formation, were deposited in basins onto and outboard of landmasses from western Gondwana (e.g., Ježek et al., 1985; Pearson et al., 2012). The Pampean arc now comprises a N-S–trending belt from southern Córdoba (~33°S) into southern Bolivia (~22°S; Aceñolaza, 2003; Drobe et al., 2009; see also Fig. 1).

The Famatinian arc started at ca. 495 Ma, presumably when subduction was reestablished along the outboard boundary of the Pampean arc and "orogeny," leaving behind in its back arc the crystalline packages metamorphosed during the Early Cambrian (Fig. 1). The southern segment (28°S to 38°S, present-day coordinates) of the Famatinian arc was closed during the middle Ordovician (beginning at ca. 465 Ma), when a continental microplate that had rifted from North American Laurentian landmasses collided against the proto-Pacific Gondwana margin (Thomas and Astini, 1996; Ramos et al., 1996).

The Famatinian arc is exposed for ~2000 km along the strike of the modern central Andes, and the transition from plutonic to volcanic Famatinian rocks can be followed over large regions in northwestern Argentina (Rapela et al., 1992; Toselli et al., 1996; Pankhurst et al., 1998; Coira et al., 1999). The deepest plutonic levels of the arc are currently exposed along a roughly N-S–striking wide belt extending ~600 km between 28°S and 33°S (Fig. 1). Complementary Early Ordovician shallow-emplaced plutonic and eruptive igneous rocks interbedded with sedimentary rocks ("Faja Eruptiva") are found within the Puna-Altiplano region (Coira et al., 1999; Viramonte et al., 2007) and in the Sierra de Famatina (Mannheim and Miller, 1996), between 22°S and 28°S. The wall rocks of all the Famatinian plutonic rocks are supracrustal sedimentary packages consisting largely of siliciclastic sediments with subordinate interlayered carbonate beds—the Puncoviscana Formation and its metamorphic equivalents (Caminos, 1979; Ježek et al., 1985; Pearson et al., 2012). As shallower levels of the Famatinian paleo-arc crust are exposed northward along strike, the non- to weakly metamorphosed sedimentary stratigraphic units mapped in the Puna and northern Sierras Pampeanas, which are correlative to the metamorphosed strata that crop to the south (Aceñolaza et al., 2000), are uncovered. Late Neoproterozoic–Early Cambrian thick turbiditic packages and Late Cambrian shallow-marine sediments are the most likely protoliths to the metamorphic units hosting the Famatinian arc plutonic rocks (e.g., Aceñolaza, 2003; Collo et al., 2009), whereas epizonal plutons in Sierra de Famatina and

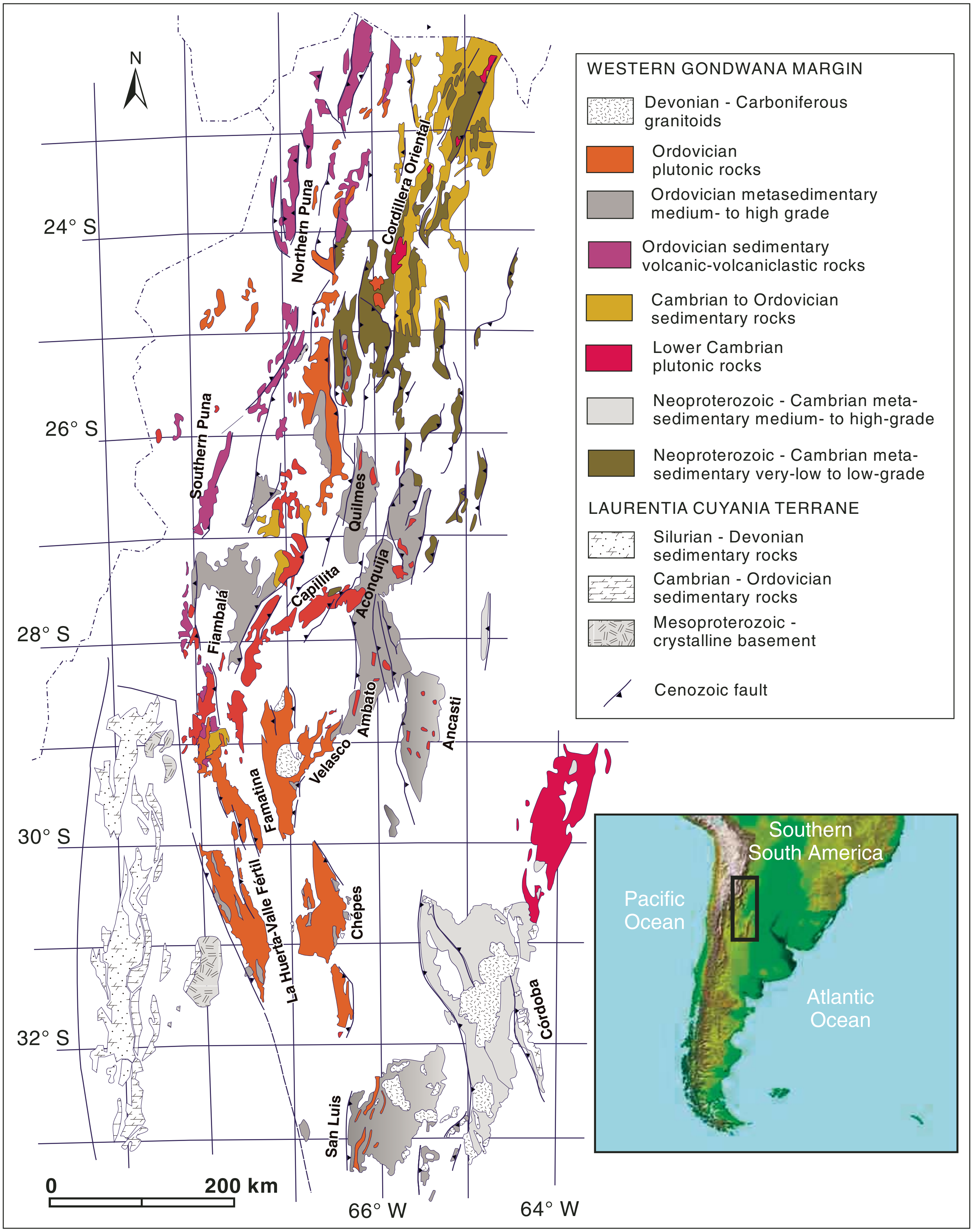


Figure 1. Map showing the distribution of pre-Carboniferous lithotectonic units in central-northwestern Argentina (modified after Pankhurst and Rapela, 1998; Coira et al., 1999; Hongn et al., 2010).

neighboring areas intruded into Early Ordovician volcanosedimentary cover sequences formed during the early magmatic arc stage of the Famatina (Toselli et al., 1996; Mángano and Buatois, 1996; Astini, 1998; Astini and Dávila, 2004).

Geology of the Sierra Valle Fértil–La Huerta Section

Within the western belt of the currently exposed Famatinian magmatic arc, the Sierra Valle Fértil–La Huerta section contains well-exposed sections showing the transition between lower- to upper-crustal levels (Fig. 2; Mirré, 1976; Vujovich et al., 1996; Otamendi et al., 2009a). In particular, cumulate textures in the mafic rocks are used as markers of paleohorizontal position (Otamendi et al., 2009a). The shallower part of the exposed section corresponds to its eastern boundary, whereas deeper levels of the crust are exposed to the west; the section is tilted almost 90° from its original position. From west to east, the lithologic units display a progression from mafic to intermediate toward more silicic igneous compositions. The overall geometry of the lower part of the section is one of numerous sills of various magmatic units that invaded a preexisting crust in which only highly migmatized residual metasedimentary rocks are found. The upper part of the exposed section contains stock-like plutons of granodiorites and rare granites that are similar to the large plutonic masses found elsewhere in Cordilleran batholiths (e.g., the Sierra Nevada in California). Only minor faults exist in this section; there is no evidence that this arc was accompanied by structural (e.g., thickening) processes while it developed. The entire Sierra Valle Fértil section was almost entirely exposed prior to the deposition of Permian–Triassic basalts. The collisional or transcollisional docking of the Cuyania-Precordillera microplate is inferred to have caused the exhumation of the deep crust in the area.

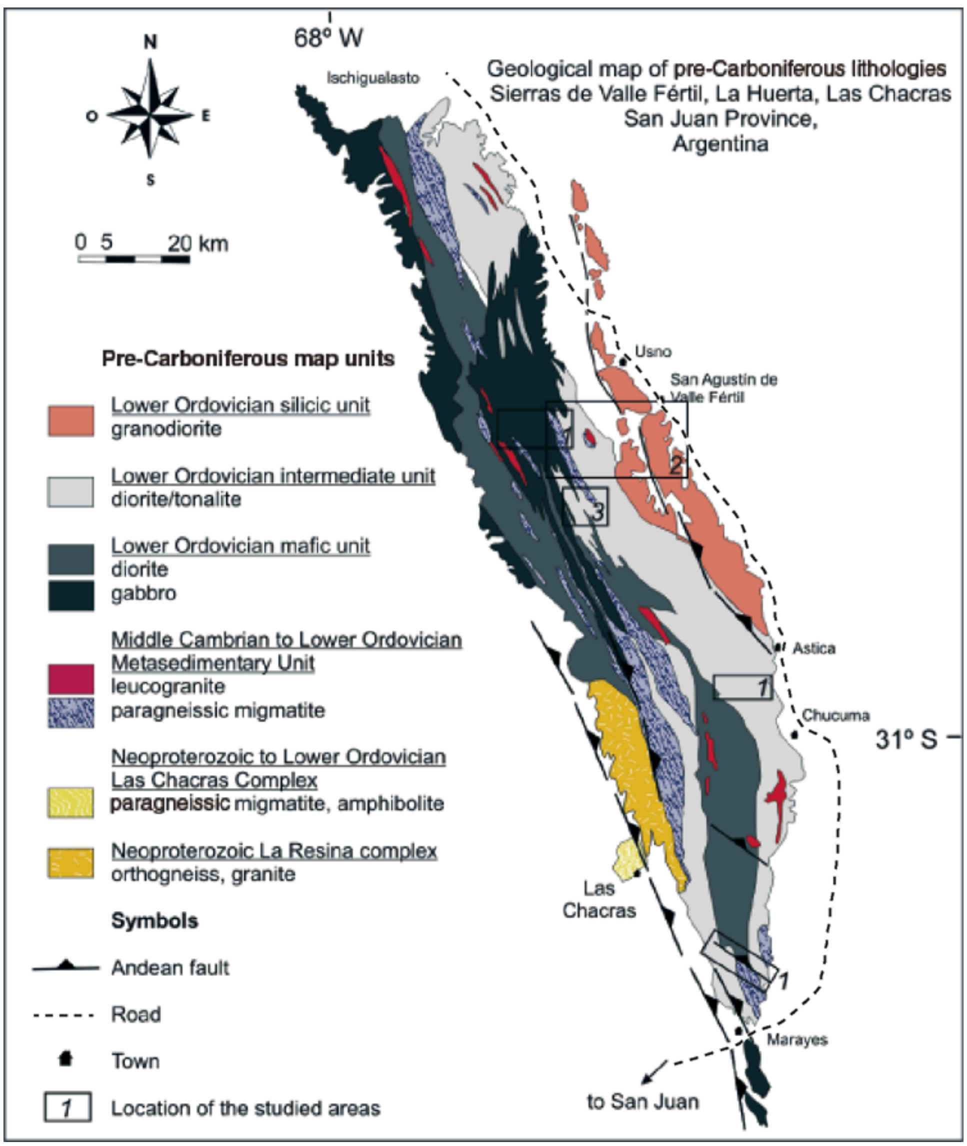


Figure 2. Simplified geologic map of the Sierras Valle Fertil–La Huerta taken after the geological maps of Mirré (1976) and Vujovich et al. (1996). Map shows the location of areas chosen in our previous studies and integrated here, these are: 1—Otamendi et al. (2009a), 2—Ducea et al. (2010) and Otamendi et al. (2012), 3—Otamendi et al. (2009b).

This deep-seated plutonic section of the Early Ordovician arc is almost entirely igneous, with minor framework of migmatitic metasedimentay rocks that were metamorphosed and partially melted during plutonism. There are no stratigraphic relationships, and mapping in the area is based entirely on magmatic-way-up indicators, metamorphic thermobarometry, and grouping of broad rocks types into rock units that predominate at various levels. The field relationships and petrographic observations and regional-scale geochemistry for every lithostratigraphic unit from the Sierra Valle Fertil has been presented in detail elsewhere (Otamendi et al., 2009a).

CHEMICAL, ISOTOPIC, AND GEOCHRONOLOGIC CONSTRAINTS ON THE PETROGENESIS OF PLUTONIC ROCKS FROM THE SIERRAS VALLE FÉRTIL–LA HUERTA

Limited Fractionation of Parental Magmas

The parental hydrous mafic magmas in the Famatinian paleo-arc have very low K_2O contents (0.2–0.4 wt%; DeBari, 1994; Otamendi et al., 2009a). Consequently, one of the most difficult compositional features of the igneous sequence to be explained by closed-system fractional crystallization is the relative covariation between K_2O and SiO_2 (Fig. 3A). In fact, this situation might be generally applicable to arcs because the great majority of primitive arc magmas have $K_2O < 0.9$ wt% (DeBari, 1994; Kelemen et al., 2003).

A simple calculation can be used to estimate the extent to which the major-element contents of the intermediate and silicic plutonic rocks are caused by closed-system fractional crystallization of primitive mafic magmas. We adopt an approach of examining K_2O and CaO versus SiO_2 trends, reflecting the fractionation of rock-forming minerals, specifically olivine, amphibole, and Ca-rich plagioclase. Pyroxenes have SiO_2 contents similar to, or even higher than, their host mafic magmas, and hence early fractional crystallization of pyroxenes alone would not generate the well-known SiO_2-enrichment trend of a subalkaline igneous series.

At pressures lower than 7 kbar, the sequence of crystallization as determined by petrographic studies is dominated by olivine + plagioclase (An > 90) ± orthopyroxene ± amphibole in primitive gabbroic magma chambers (Otamendi et al., 2010) and amphibole + plagioclase (An_{80}–An_{60}) in the gabbronoritic to dioritic magma bodies (Otamendi et al., 2009a). The increase of SiO_2 in the derivative magma is caused by fractional crystallization of olivine, calcic plagioclase, and/or amphibole (Foden and Green, 1992; Eichelberger et al., 2006; Larocque and Canil, 2010). Olivine is the first ferromagnesian phase to crystallize in the most primitive rocks, but the appearance of olivine is limited to mafic-ultramafic cumulate layered bodies (Otamendi et al., 2010). This observation suggests that olivine cannot govern the crystallization sequence outside primitive magmatic chambers, and rules out olivine as part of the main assemblage controlling differentiation of arc magma from gabbro through diorite to tonalite and granodiorite.

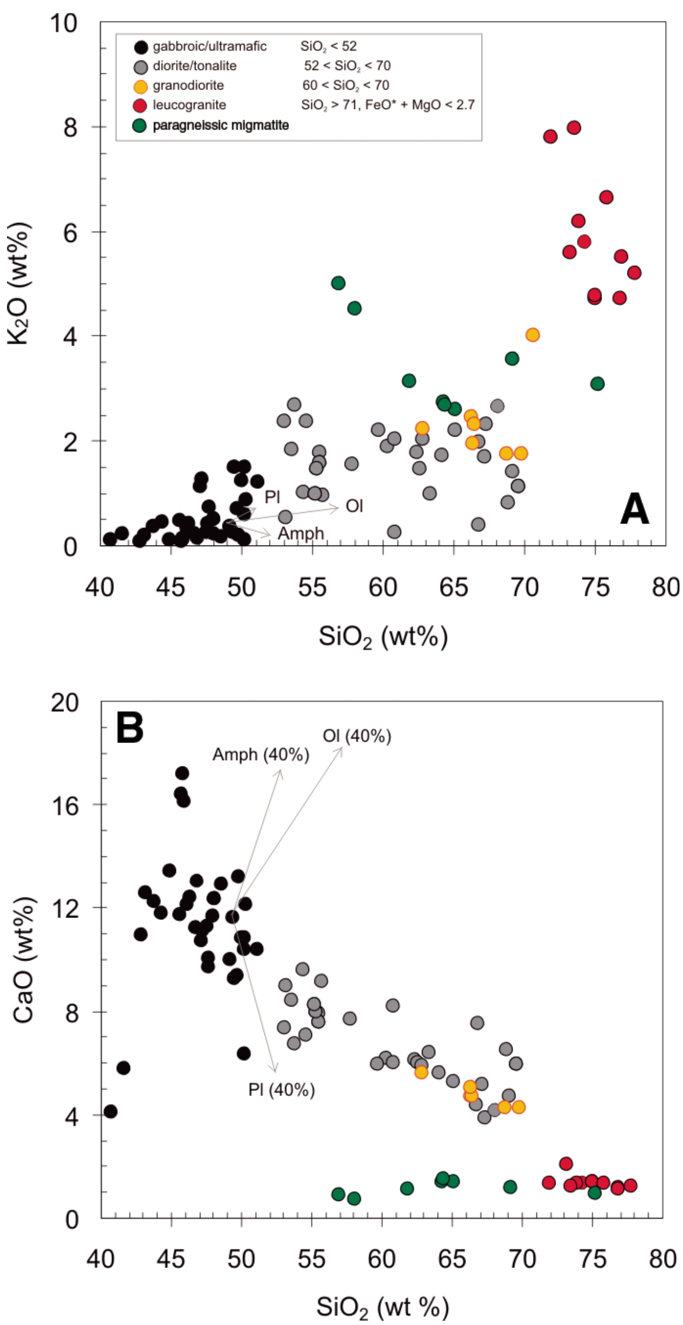


Figure 3. Representative whole-rock compositional variation for plutonic, metasedimentary, and anatectic granitic rocks from Sierras Valle Fertil–La Huerta shown in (A) K_2O and (B) CaO Harker-type diagrams. Vectors shows the compositional changes caused by fractional crystallization of distinct rock-forming minerals and the evolution of liquid after removing 40 wt% of a given mineral. Pl—plagioclase; Amph—amphibole; Ol—olivine.

In compositional terms, the effects of amphibole fractionation are broadly similar to those of olivine. The difference is that amphibole is found throughout the crystallization sequence, which makes amphibole the best candidate for driving the SiO_2-enrichment trend (Foden and Green, 1992; Larocque and Canil, 2010). Amphibole fractionation alone, however, cannot account for the well-defined decrease of CaO and increase of K_2O with increasing SiO_2 (Figs. 3A and 3B). To some extent, the combination of plagioclase and amphibole as early fractionating phases may replicate the igneous evolutionary trend, because the incorporation of K_2O in plagioclase is much lower than that of the magma (Fig. 3A). However, the CaO abundance of intermediate plutonic rocks is typically higher than 3.8 wt% and sets a limit to the proportion of calcic plagioclase involved in the process of fractional crystallization (Fig. 3B). A simple mass balance shows that if plagioclase fractionation were higher than 50%, the derivative magma would have CaO lower than those of the typical intermediate rocks, and even this proportion of plagioclase fractionation (50%) is not enough to yield the K_2O content of common intermediate rocks. In contrast, the linearity of geochemical data as seen in the Harker variation diagrams is commonly attributed to two-component magma mixing (Reid et al., 1983; Gray, 1984).

The K_2O contents of the Valle Fertil plutonic belt are not easily accounted for without involving a supracrustal (metasedimentary or its derivative granites) precursor in their ancestry. This is a common problem of calc-alkaline Cordilleran granites that was strikingly revealed by comparing various experimental petrology results with natural arc rocks (e.g., Patiño Douce, 1999).

Age Pattern of Inherited Zircon from the Plutonic Rocks

The age spectra of inherited zircon in the intermediate to silicic plutonic rocks provide an independent line of evidence for testing the ancestry of source materials of the igneous rocks from the Famatinian-Puna arc. The only area that has been investigated in detail for that purpose is the Valle Fertil section in the Sierra Pampeanas.

In a recent study (Ducea et al., 2010), we determined that inherited zircon cores within the plutonic rocks from Valle Fértil fingerprint several early magmatic events and cover the spectrum from Late Archean to early Paleozoic orogenic cycles. That paper provides a detailed study of zircon age populations for 15 plutonic rocks from the Sierra Valle Fértil; here, we evaluate the nature of inheritance in plutonic rocks by pooling the population of zircon ages older than 520 Ma from that study (Figs. 4A–4C). This cutoff age was chosen because it would date igneous or metamorphic events predating the first manifestation of the typical Famatinian magmatism, but it would still be able to record the late stage of the Pampean "orogeny" (e.g., Pankhurst and Rapela, 1998; Hongn et al., 2010). Figures 4A–4C show the histograms of age data and probability plots for representative individual plutonic rocks, which were then combined to construct the inherited zircon pattern for a composite of 12 tonalites and granodiorites. The pattern of inherited zircon cores pooled from plutonic rocks from the Sierra Valle Fértil confirms at least three well-defined clusters of ages at around 1090, 600, and 530 Ma (see Fig. 4, lowest panel). Overall, this inheritance of zircon ages is typical and characteristic of three tectono-magmatic orogenic systems that were active from the Mesoproterozoic to the Early Cambrian in western Gondwana (de Brito Neves and Cordani, 1991; Trompette, 1997; Rapela et al., 2007; Adams et al., 2008; Drobe et al., 2009; Collo et al., 2009).

The Early Ordovician plutonism from the Sierra Valle Fértil was built up into a supracrustal sedimentary sequence that filled basins outboard of a western Gondwanan landmass (e.g., Ducea

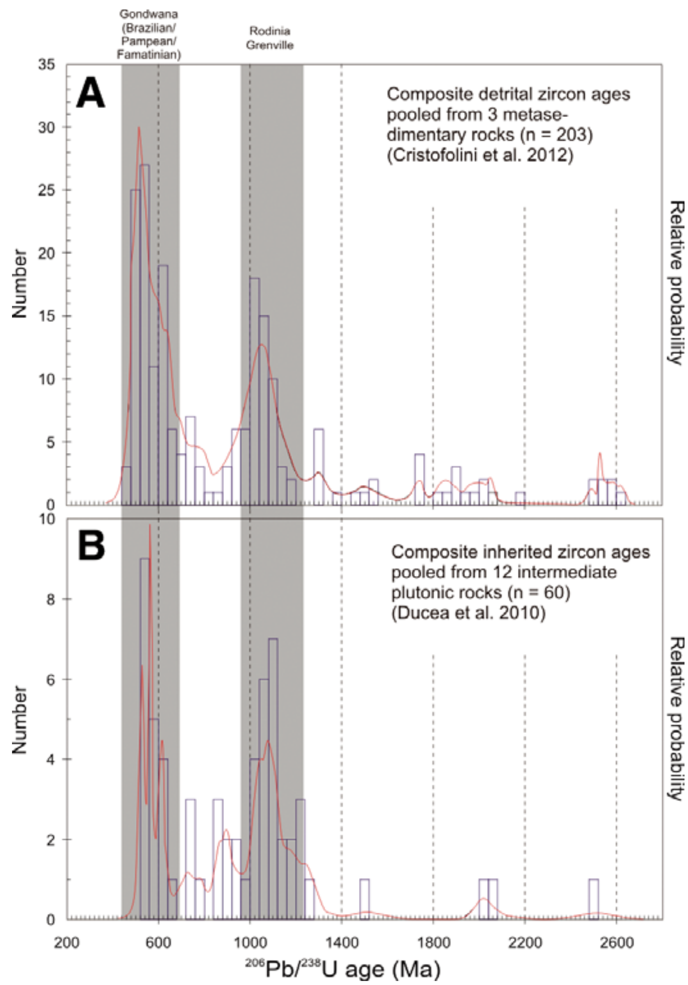


Figure 4. Combined histograms and probability plots illustrating the age data for metasedimentary and igneous rocks from the Sierra Valle Fertil. These plots were constructed with Isoplot 3.00 by Ludwig (2003). The number of analyses (*y* axis) gives the number of ages that fall in each histogram bin. Along the *x* axis, each plot covers a range in ages from 200 to 2800 Ma with 40 m.y. bin widths. These histograms are overlain by true probability plots for each of the age ranges. (A) Histogram of detrital zircon ages taken after Cristofolini et al. (2012). (B) Histogram of inherited zircon ages of plutonic rocks constructed using 14 specimens (Ducea et al., 2010).

et al., 2010). The spectra of inherited zircon ages preserved within the plutonic rocks reveal that the intermediate and silicic magmas had incorporated a significant amount of a (meta)sedimentary component, on average around 50% (±20%), based on a mass balance using Sr and Nd isotopes. The incorporation of inherited zircons must have resulted from widespread partial to nearly complete melting of pelitic and semipelitic host rocks and subsequent assimilation into the evolving magmas.

Modeling Radiogenic Isotopic Variations

A correlation exists between $\varepsilon_{Nd(i)}$ and $^{87}Sr/^{86}Sr_{(i)}$ among rock types and their isotopic composition, because a systematic trend of isotopic enrichment ranges from the igneous mafic to the metasedimentary migmatites and their anatectic leucogranitic complements (Fig. 5). Dioritic rocks define a cluster of isotopic data that appears nearly in the middle of the $\varepsilon_{Nd(i)}$ versus $^{87}Sr/^{86}Sr_{(i)}$ array between mafic and metasedimentary migmatites. Tonalitic rocks are isotopically more evolved than dioritic rocks in the Famatinian-Puna belt; however, the scatter of data for tonalites contrasts with a well-defined cluster displayed by diorites.

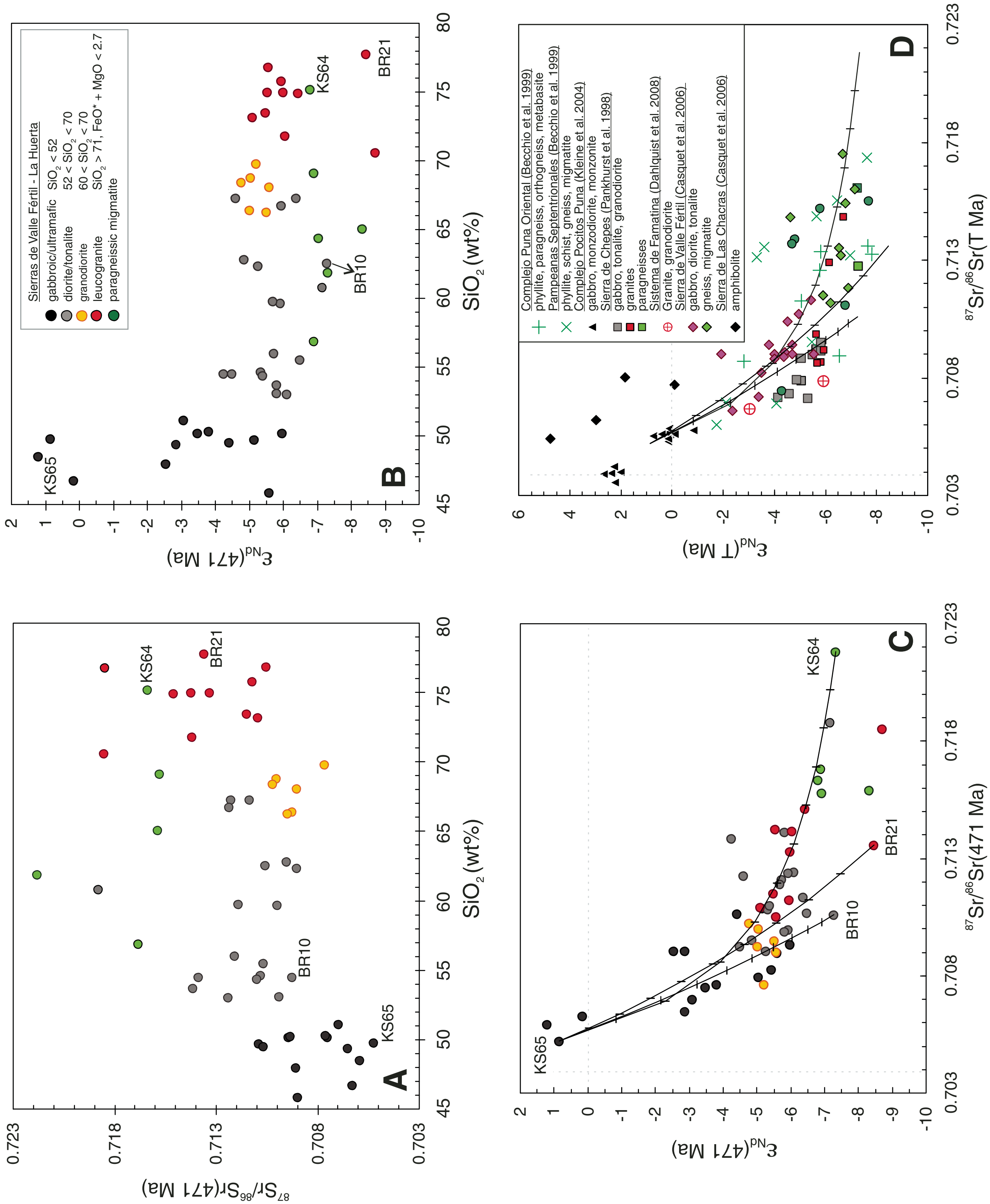
Despite the scatter of data, the initial ε_{Nd} and Sr isotopic compositions of rocks from the Famatinia-Puna arc display the hyperbolic trend characteristic of many arc plutonic suites in which the local upper plate contributes to the mass balance of the arc via assimilation (DePaolo and Wasserburg, 1979; McCulloch and Chappell, 1982; Gray, 1984). The most plausible interpretation for this data array is that the overall isotopic compositions reflect mixing between two end-member components. As a test for mixing, Figure 5 shows the projection of two mixing lines connecting the isotopically most primitive mafic rocks with either a metasedimentary migmatite or an anatectic leucogranite derived from partially melting metasedimentary rocks. The observation that several plutonic rocks fall within the band predicted by different two-component mixing hypotheses suggests that each plutonic rock is a hybrid product between a mantle-derived component and some (supra)crustal material, and that isotopic differences among rocks result from variable proportions of end-member components in the mixture (e.g., Gray, 1984).

Most primitive gabbroic rocks from Pocito and Valle Fértil–La Huerta suggest that the mafic component involved regionally in the Famatinian arc is isotopically enriched (Fig. 5; also see Kleine et al., 2004; Otamendi et al., 2012; Casquet et al., 2006). This reflects the existence of an ancient incompatible element–enriched subcontinental lithospheric mantle residing beneath the Early Ordovician arc. An alternate possibility is incorporation of melts and/or fluids released by the subducted sediments and oceanic crust into the mantle wedge. We do not favor the second hypothesis because, as shown elsewhere (e.g., Ducea and Barton, 2007), it would be unlikely to modify the isotopes (especially Nd isotopes) by slab-wedge interaction and still produce primitive mafic rocks. The primary material that makes up the mantle-derived component in this arc is continental lithosphere.

The most obvious candidate for a crustal end member is represented by the widespread Neoproterozoic to Early Cambrian Puncoviscana trough sedimentary sequences (Ježek et al., 1985; Mángano and Buatois, 2004; Zimmermann, 2005) or their metamorphic equivalents (Rapela et al., 1998; Becchio et al., 1999) and the Late Cambrian to Early Tremadocian formations, broadly known as Mesón Group, Negro Peinado, and La Aguadita (Aceñolaza, 2003; Collo et al., 2009). All of these sedimentary sequences were buried, and thus they hosted and interacted with Early Ordovician magmatism. In contrast, post-Tremadocian sedimentary sequences are excluded as potential sources of crustal granites because they are coeval with or even younger than the main plutonic arc activity (Mángano and Buatois, 1996; Bahlburg, 1998; Zimmermann and Bahlburg, 2003). Both Sr and Nd isotopes have been measured in metasedimentary rocks metamorphosed from greenschist- to granulite-facies conditions (Rapela et al., 1998; Becchio et al., 1999; Pankhurst et al., 1998). As the Sr- and Nd-isotopic compositions broadly overlap within the scatter of data, the sedimentary packages metamorphosed during the Early Cambrian (i.e., Pampean arc) and Early Ordovician (i.e., Famatinian-Puna arc) can be considered as a single isotopic component. These metasedimentary packages typically have initial $^{87}Sr/^{86}Sr$ higher than 0.713 and a wide range of $\varepsilon_{Nd(i)}$, from –3 to –10. The Late Cambrian low-grade metasedimentary sequence from Famatina has broadly the same $\varepsilon_{Nd(i)}$ values as those measured in schists and gneisses from the northern Sierras Pampeanas (Collo et al., 2009).

Purely granitic magmas generated after partially melting the fertile metasedimentary sequences, as suggested earlier, are a second crustal component for contaminating the evolving lineage of mantle-derived magmas. In terms of isotopic signature, strict granitic rocks seem to be divisible into two groups. One group of these granites clearly lies inside the isotopic compositional field of the metasedimentary sequences (Fig. 5). Therefore, as suggested by their whole-rock compositions, these granites crystallized from magmas solely generated after partially melting metasedimentary packages (Dahlquist et al., 2005). In contrast, some granite from the Sierra de Chepes studied by Pankhurst et al. (1998) has initial $^{87}Sr/^{86}Sr$ values much lower than those of typical metasedimentary rocks.

Regardless of the actual crustal contaminant, interaction between mafic magmas and upper-plate (local crust) supracrustal material provides the easiest explanation for the origin of intermediate and silicic plutonic rocks. The great majority of the intermediate and silicic plutonic rocks from the Famatinian-Puna arc appear nearly in the middle of the $^{87}Sr/^{86}Sr_{(i)}$–$\varepsilon_{Nd(i)}$ hyperbolic array between mafic primitive and metasedimentary/granitic components (Fig. 5). The lack of measurement of one isotopic system impedes projection of many other plutonic and volcanic rocks that either have $^{87}Sr/^{86}Sr_{(i)}$ between 0.706 and 0.710 (Mannheim, 1993; Saal et al., 1996; Saavedra et al., 1996) or $\varepsilon_{Nd(i)}$ between –2 and –6 (e.g., volcanosedimentary successions in Bock et al., 2000), but several of these Early Ordovician igneous rocks would most likely lie on the middle of the hyperbolic trend predicted


A
B
C
D
SiO2 (wt%)
87Sr/86Sr(471 Ma)
εNd(471 Ma)
εNd(T Ma)
87Sr/86Sr(T Ma)
KS65
KS64
BR10
BR21
Sierras de Valle Fértil - La Huerta
gabbroic/ultramafic SiO2 < 52
diorite/tonalite 52 < SiO2 < 70
granodiorite 60 < SiO2 < 70
leucogranite SiO2 > 71, FeO* + MgO < 2.7
parageissic migmatite
Complejo Puna Oriental (Becchio et al. 1999)
phyllite, parageiss, orthogneiss, metabasite
Pampeanas Septentrionales (Becchio et al. 1999)
phyllite, schist, gneiss, migmatite
Complejo Pocitos Puna (Kleine et al. 2004)
gabbro, monzodiorite, monzonite
Sierra de Chepes (Pankhurst et al. 1998)
gabbro, tonalite, granodiorite
granites
parageisses
Sistema de Famatina (Dahlquist et al. 2008)
Granite, granodiorite
Sierra de Valle Fértil (Casquet et al. 2006)
gabbro, diorite, tonalite
gneiss, migmatite
Sierra de Las Chacras (Casquet et al. 2006)
amphibolite

by the two-component mixing model. Our partial compilation of isotopic data gives evidence that most of the diorites, tonalites, granodiorites, and some monzogranites from the Famatinia-Puna arc fall on the hyperbola of two-component mixing where the end members are a primitive mafic igneous suite and a crustal material. However, we avoided modeling a particular case, because it has been shown that the mixing process is neither a single-step mechanism nor solely moved by magma mixing (Eichelberger et al., 2006). In effect, some middle member of the igneous suite may derive by hybridization in which one member is already a hybrid product between the two extreme end members (Beard, 2008; Otamendi et al., 2009b). Isotope variations would thereby reflect the end result of more complex petrogenetic mechanisms than two-component mixing, but in fact every single plutonic rock embodies the two components mixed at variable proportions. Moreover, the evidence extracted from isotopes is perfectly consistent with conclusions made from observing major-element variations. Also significant is that, at deep-seated levels from the Early Ordovician paleo-arc crust, there are observable field relationships supporting the occurrence of open-system processes (Otamendi et al., 2009b). Finally, the juvenile mafic and the crustal metasedimentary end members seem to be universal, as they have been found to play their role in most of the worldwide recognized Cordilleran-style plutonic chains, such as the Sierra Nevada and Peninsular Range (DePaolo, 1981; DePaolo et al., 1992; Pickett and Saleeby, 1994), and the Lachlan fold belt (Gray, 1984; Collins, 1996; Keay et al., 1997; Kemp et al., 2009).

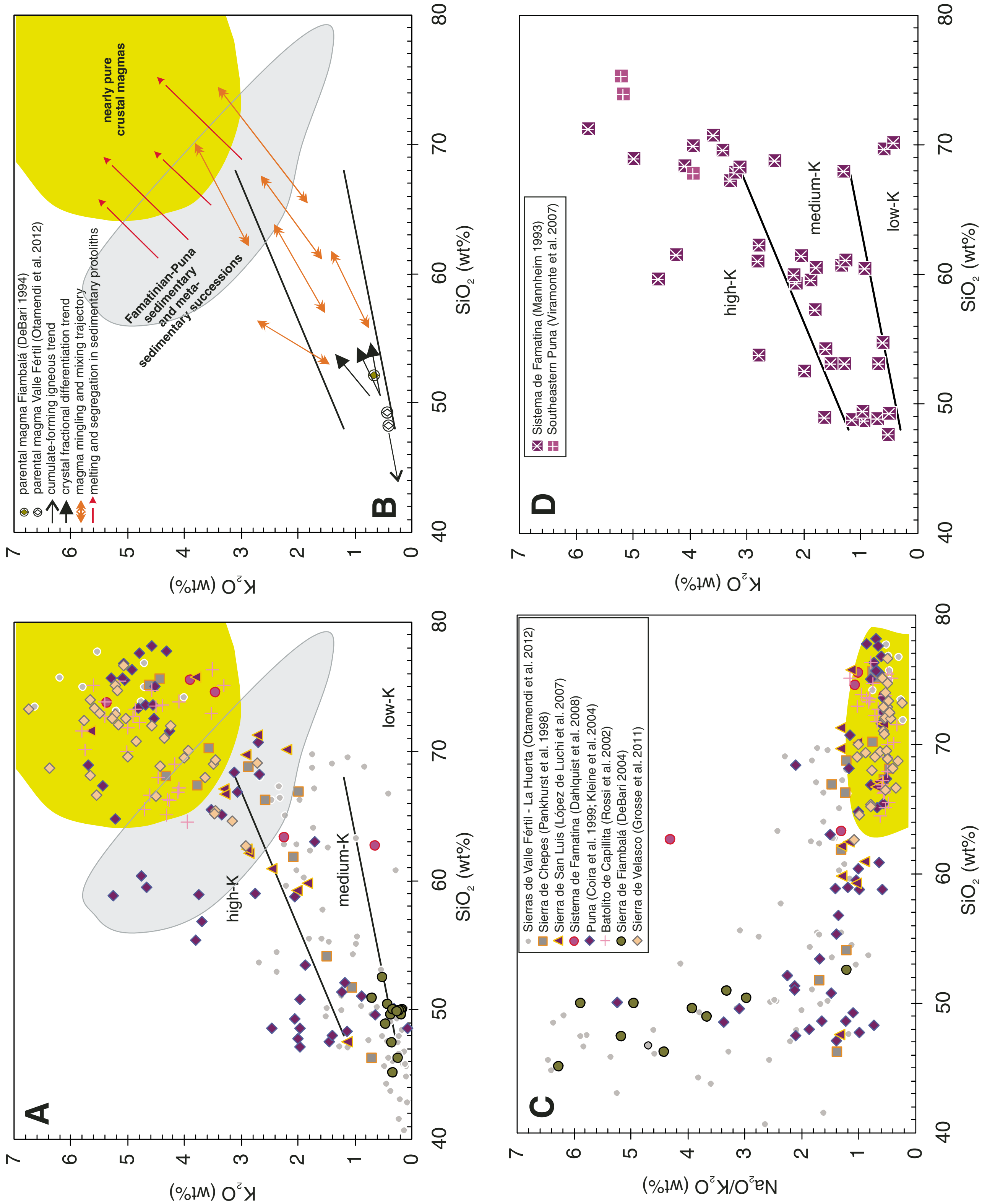
PETROLOGIC IMPLICATIONS

Data for the high-grade partially melted metasedimentary rocks from Valle Fértil and La Huerta exhibit remarkably similar major-element contents to those of the medium- and low-grade metasedimentary rocks and sedimentary rocks elsewhere in the Early Ordovician magmatic belt (Fig. 6A). All these metasedimentary and sedimentary rocks define linear arrays for most major oxides against silica, reflecting the fact that they encompass pelites (SiO_2 ~59 wt%) to quartz-rich graywackes (SiO_2 ~80 wt%). Within the major-oxide covariant diagrams, the high-grade metasedimentary rocks from Valle Fértil and La Huerta fall across the low-potassium limit, which is consistent with their having undergone partial melting and melt loss (Fig. 6A). Major-element whole-rock compositions do not provide solid constraints for correlating sedimentary rocks, because the chemistry of sediments reflects the mechanical unmixing of clay and sand that takes place in every sedimentary cycle (Taylor and McLennan, 1985). However, the correlation of major elements strongly suggests that the sedimentary packages that were stacked, buried, and metamorphosed between the Late Neoproterozoic and Early Ordovician had broadly similar sedimentary sequences of facies to those that remained in the upper crust (Fig. 6A). A sedimentary sequence made up by alternating beds of pelites and graywackes has the largest potential to produce granitic melts when experiencing granulite-facies temperatures (Thompson, 1996). By implication, the combination of fertility and volume of the Late Neoproterozoic and Early Ordovician sedimentary packages can account for all the felsic weakly and strongly peraluminous granites from the Ordovician system. Granitic batholiths entirely made up by peraluminous granitoids document that massive crustal anatexis occurred where a large-scale heat input acted upon widespread metasedimentary sequences (Rossi et al., 2002; Dahlquist et al., 2005). Our compilation of data also shows that metasediment-derived granites appear in almost all of the localities from the Early Ordovician magmatic system, and hence reflect crustal anatexis that took place pervasively at lower- to middle-crustal levels of the Famatinian-Puna paleo-arc (Fig. 6B). The importance of this interpretation, as inferred from field and compositional observations, is that metasediment-derived granites derived from partial melting of the upper plate are an essential component for driving the igneous evolutionary trend from gabbroic to monzogranitic rocks.

However, intracrustal melting of the metasedimentary sequence alone does not explain the vast volume of plutonic and volcanic rocks from the Early Ordovician magmatic belts. The plutonic suite spanning the range from gabbros to monzogranites has MgO, FeO, and CaO contents as well as Na_2O/K_2O ratios that are too high to be derived from any siliciclastic sedimentary protolith (e.g., Patiño Douce, 1999). Contrasting with the relative compositional homogeneity of the crustal granites, the igneous suite from gabbros to monzogranite spreads over a wide range of petrographic and chemical rock types (Figs. 6B and 6C). In effect, the nature of the latter suite of igneous (plutonic and volcanic) rocks needs to be further evaluated in the Early Ordovician magmatic belts.

Typical localities within the Famatinia-Puna magmatic arc consist of igneous rock suites with a compositional trend of increasing K_2O with increasing SiO_2 (Fig. 6B). This trend is also a distinctive characteristic of the Valle Fértil–La Huerta igneous suite and, as shown already, requires, to a large extent, a driving mechanism by crustal contamination of the evolving igneous magmas. As Figure 3A illustrates, at some point in the generation of the Early Ordovician igneous suites, every rock more evolved than a typical diorite must have incorporated a crustal component

Figure 5. Isotopic composition of rocks from Sierras de Valle Fertil–La Huerta compiled after Otamendi et al. (2009a, 2010, 2012). (A) Variation of $^{87}Sr/^{86}Sr$ at 471 Ma vs. SiO_2. (B) Variation of ε_{Nd} at 471 Ma vs. SiO_2. (C) Plot of ε_{Nd} vs. $^{87}Sr/^{86}Sr$ ratios (at 471 Ma) for plutonic rocks, metasedimentary migmatites, and anatectic and leucogranites. Hypothetical mixing models were computed using a primitive gabbroic rock and three potential crustal components. Mineralogy and whole-rock compositions of end-member rocks were provided in our previous studies. Tick marks on mixing lines are at 0.1 end-member fractions. (D) Plot of ε_{Nd} vs. $^{87}Sr/^{86}Sr$ ratios (at reported crystallization age) for rocks in type localities from the Famatinian-Puna arc. The geographic position of each locality is shown in Figure 2. Insets give the data sources for each locality. The three mixing lines computed for Valle Fertil and La Huerta rocks are shown for comparison.


A
high-K
medium-K
low-K
K_2O (wt%)
SiO_2 (wt%)
B
parental magma Fiambalá (DeBari 1994)
parental magma Valle Fértil (Otamendi et al. 2012)
cumulate-forming igneous trend
crystal fractional differentiation trend
magma mingling and mixing trajectory
melting and segregation in sedimentary protoliths
nearly pure crustal magmas
Famatinian-Puna sedimentary and meta-sedimentary successions
C
Sierras de Valle Fértil - La Huerta (Otamendi et al. 2012)
Sierra de Chepes (Pankhurst et al. 1998)
Sierra de San Luis (López de Luchi et al. 2007)
Sistema de Famatina (Dahlquist et al. 2008)
Puna (Coira et al. 1999; Kleine et al. 2004)
Batolito de Capillitas (Rossi et al. 2002)
Sierra de Fiambalá (DeBari 2004)
Sierra de Velasco (Grosse et al. 2011)
Na_2O/K_2O (wt%)
D
Sistema de Famatina (Mannheim 1993)
Southeastern Puna (Viramonte et al. 2007)

through either assimilation of metasedimentary rocks or interaction with metasediment-derived melts.

A significant volume of Early Ordovician magmatism erupted as either lava flows or pyroclastic rocks (Mannheim, 1993; Mannheim and Miller, 1996; Coira et al., 1999; Zimmermann and Bahlburg, 2003; Viramonte et al., 2007; and references therein). Field relationships are unequivocal about the complementary nature between Early Ordovician plutonic and volcanic rocks. In addition, the few available data for Famatinian-Puna volcanic rocks show compositional similarity with plutonic rocks (Fig. 6D). Thus, the same petrologic mechanisms as those observed for plutonic rocks were responsible for governing the whole-rock composition of eruptive volcanic sequences, with a slightly higher K_2O at a given content of SiO_2 for the volcanics.

IMPLICATIONS FOR CONTINENTAL ARC MAGMATISM

The Famatinian arc was clearly a continental arc, as it straddles the western margin of Gondwana in the modern coordinates of South America. There is no evidence that the South American cratonic basement crust was involved in magmatism in the Sierra Valle Fertil region; instead, the arc was emplaced exclusively into an extensive sedimentary assemblage that most likely constituted the accumulation of submarine passive-margin sediments along Gondwana's margin during the Neoproterozoic and early Paleozoic prior to subduction. However, all gabbros that have been analyzed in this section have radiogenic isotopic characteristics typical of old (Precambrian) continental lithosphere (Otamendi et al., 2009a, 2012), suggesting that South American lithosphere, perhaps thinned at a miogeoclinal margin, was in fact the framework of this arc. There is also no evidence that the crust became unusually thick during the Famatinian arc magmatism, as no rocks deeper than ~25–30 km are exposed at the surface to the west of the studied area, based on our preliminary field observations and mapping of index minerals within metamorphic framework rocks, or elsewhere within the exposed plutonic framework of the Famatinian arc in central South America. In addition, there is also no evidence for crustal magmas (felsic plutons or volcanics) that were derived from thicker parts of the crust. No shortening or extension disrupted the architecture of the section studied here during arc formation. Instead, the arc developed statically as a series of sills progressively emplaced into the existing crust, similar to the early stages (Jurassic) of Cordilleran magmatism in North America and to Cordilleran interior arcs that developed in North America during periods of shallow subduction as magmatism migrated inland (Barton, 1996).

We show that magmatic input from the mantle at an average rate of mafic arc magmatism worldwide (Ducea and Barton, 2007) can provide enough heat and mass available for mixing with a preexisting metamorphic basement to generate a batholith-scale crustal section within a short period of time, some 15 m.y. or less. The architecture of the arc is one of multiple tens- to hundreds-of-meters-thick amphibole-rich gabbroic sills injected into a midcrustal section, where they mixed with partial melts derived from a metasedimentary framework. All mantle-derived melts intruded in the section were wet gabbros, and magmatic fractionation trends observable through field relationships suggest that some of these bodies transitioned to mafic diorites in their upper parts via closed-system fractionation. There is no evidence that gabbros in this section fractionated to intermediate (higher silica) rocks, nor is there evidence that they ever remelted to generate more felsic melts. A signature feature of the entire Sierra Valle Fertil area is that virtually every outcrop in which we observe transitions from the mafic to tonalitic/granodioritic rocks is in close proximity to a metasedimentary pendant or contains "ghosts" of it (identifiable rock enclaves, areas rich in cordierite and almandine garnet) within the more felsic units. Thus, we use our extensive field observations at the scale of this study and a moderate knowledge of the entire range to state that, with the exception of local closed-system fractionation to mafic diorite of gabbroic sills, the entire compositional diversity of the Famatinia-Puna arc—which includes the full compositional spectrum of Cordilleran calc-alkaline suites such as quartz diorites, monzonites, tonalites, granodiorites, and granites—was generated by various hybridization processes between mantle-derived gabbros and diorites and the Puncoviscana metasedimentary rocks and their high-grade equivalents.

We suggest that any incipient arc that developed on a continental upper plate in a subduction system may have similar characteristics to the Famatinian-Puna arc. They are static arcs emplaced as a series of mafic sills that ignite melting of and mixing with their framework rocks at magmatic rates that can be higher than 100 $km^3/km/m.y.$, depending on the extent to which the framework is melt fertile (e.g., Annen and Sparks, 2002). The late Paleozoic and early Mesozoic arcs of the North American Cordillera are equivalents to the Famatinian arc. In addition, island arcs emplaced into crust that experience long-lived subduction and have sizable trench and forearc accumulations (like modern Japan, the Caribbean, and parts of the Aleutians) where the upper plate is continental may have a similar crustal architecture.

Figure 6. (A) Plot of K_2O vs. SiO_2 for plutonic and volcanic rocks in the Famatinian-Puna magmatic arc. The positions of lines separating low-, medium-, and high-K fields in the K_2O vs. SiO_2 diagram are taken after LeMaitre et al. (1989). (B) Schematic representation of petrologic process in the K_2O vs. SiO_2 covariation system. (C) Plot of Na_2O/K_2O ratios for same rocks as in panel A. (D) Plot of K_2O vs. SiO_2 for volcanic rocks in the Famatinian-Puna magmatic arc.

CONCLUSIONS

1. Field relationships, the pattern of inherited zircon ages, and whole-rock compositional (elemental and isotopic) evidence clearly indicate that crustal contamination accompanying fractional crystallization explains the genesis of intermediate and silicic plutonic rocks of the Famatinian arc; on average a mixture

of ~50% mantle-derived gabbros and 50% crustal melts is suggested by field relationships in the Sierra Valle Fertil and is consistent with geochemical data.

2. Virtually every igneous rock more evolved than gabbros or basalts has been contaminated with a (supra)crustal component; model ages from all intermediate and silicic igneous rocks reflect the mixture between a Grenville-aged average crustal source and an underlying old continental mantle wedge.

3. The lithospheric architecture of the modern Cordilleran interior of the central Andes, including the Altiplano-Puna Plateaus, the Eastern Cordilleran region, and the western Sierras Pampeanas, has been profoundly influenced by the development of the Famatinian-Puna arc.

4. The Famatinian-Puna arc is an ancient equivalent of arcs formed on thin continental lithosphere covered by thick miogeoclinal sequences soon after subduction initiation.

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