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Ultrafast magmatic buildup and diversification to produce continental crust during subduction

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ABSTRACT

The processes and fluxes that produce the distinct compositional structure of Earth's continental crust by subduction remain controversial. The rates of oceanic crust production, in contrast, are well quantified and are generally believed to be faster than those responsible for building magmatic systems in subduction settings. Here we show that a recently recognized crustal section, the 30-km-thick Ordovician Sierra Valle Fértil–Sierra Famatina complex in Argentina, was built magmatically within only ~4 m.y. More than half of the crustal section represents additions from the mantle, and is preserved as mafic igneous rocks and mafic-ultramafic cumulates; the remainder is tonalite to granodiorite with evidence for widespread assimilation from highly melted metasedimentary units. U-Pb zircon geochronology reveals that the construction of the arc was not a simple bottom-up construction process. This continuous exposure of the arc crust allows the quantification of field constrained magmatic addition rates of 300–400 km^3 km^{-1} $m.y.^{-1}$. These rates are similar to those determined for modern slow-spreading mid-ocean ridges and are of the same magnitude as magmatic addition rates required to build certain large segments of the continental masses such as the Arabian-Nubian shield, among others. The implication is that significant convective removal of arc roots is required over time in order to build the modern continental crust via subduction-related magmatism.

INTRODUCTION

Subduction-related arc magmatism is regarded to be one of the main mechanisms responsible for generating intermediate composition continental crust over geologic time (Taylor and McLennan, 1985; Hawkesworth and Kemp, 2006; Jagoutz, 2014). Despite extensive experimental and observational work on magmatism at convergent margins (Eichelberger, 1978; Grove et al., 2012; Stern, 2002), the controls and time scales producing compositional diversification such as rates of melting (slab, mantle wedge, mantle lithosphere, and upper plate crust) and involvement of the upper crustal plate remain highly controversial (Ducea et al., 2015a). Mantle-derived magmatic fluxes are not well constrained (Jicha and Jagoutz, 2015; Ducea et al., 2015b) and we lack a unifying mechanism for quantifying melting in and above subducting slabs. Direct geological evidence for basalt–upper plate interaction is hampered by sparse field exposures of the lower parts of the subduction system, in particular the lower crust (Salisbury and Fountain, 1990; Hacker et al., 2015).

The recently discovered Sierra Valle Fértil crustal arc section (Otamendi et al., 2009) is, in combination with the neighboring Sierra Famatina (Astini and Dávila, 2004; Tibaldi et al., 2013), one of the best quasi-continuous vertical exposures of a subduction-related continental magmatic arc on Earth (Fig. 1). Here we combine newly obtained and previously published geochronology, field geology, and geobarometry data to extract critical magmatic addition rate (Reymer and Schubert, 1984) parameters that help our overall understanding of magmatism in arcs. We show that a thickness of ~30 km of arc crust was entirely built by magmatic processes within ~4 m.y., much faster than most predictions, although in line with some very recent results from other arcs (Jicha and Jagoutz, 2015) and potentially significant to understanding the production of continental crust over time.

GEOLOGIC BACKGROUND

The Sierra Valle Fértil is an ~150-km-long, ~30-km-wide range exposing exclusively basement rocks that represent a tilted section through the Ordovician Famatinian-Puna arc (Pankhurst et al., 1998). The Famatinian-Puna arc (Ducea et al., 2015c) is a subduction-related magmatic arc found in several other Sierras Pampeanas ranges, notably the nearby Sierra Famatinia (the type locality for the Famatinian arc), and extends discontinuously for a length >2000 km from southern Peru to Patagonia. Sierra Valle Fértil geology is relatively uniform along strike (Fig. 1) and it represents an intact tilted section of the Famatinian arc from ~30 km paleodepths along the western margins to ~8 km along its eastern margin (Tibaldi et al., 2013). Volcanic rocks of the arc are exposed in the Sierra Famatinia, immediately to the northeast. A fault-bound basin formed during Permian–Triassic continental extension separates the two ranges. To the west, the section is cut by the Valle Fértil lineament, a major shear zone representing a terrane boundary (Mulcahy et al., 2014). The deepest exposure levels of the Famatinian arc there (Tibaldi et al., 2013), based on the geochemistry of felsic plutons higher in the section (Otamendi et al., 2012; Walker et al., 2015), overall coincide with the lowest part of the arc crust.

The upper part of the Sierra Valle Fértil section is dominated by I-type granodiorites and lesser amounts of tonalite, together amounting to intrusive volumes on the scale of a composite batholith (Fig. 1), very similar to the major Mesozoic and younger Cordilleran (Andean) arcs of North America and South America. The Famatinian arc is for the most part isotopically enriched, i.e., has elevated initial isotopic ratios of $^{87}Sr/^{86}Sr$ (>0.706) and negative initial ε_{Nd} (<–2), similar to the modern central Andes (Otamendi et al., 2009; Walker et al., 2015). These isotopic characteristics are seen in mafic rocks just as in higher silica intermediate or felsic magmas (Ducea et al., 2015c). The section transitions downward to mafic rocks (gabbros and diorites) and mafic and ultramafic cumulate. The total thickness of mafic and ultramafic units is ~10 km; however, because many of those units are cumulates and a fraction of the mass of mafic input was incorporated in the more intermediate products found closer to the arc surface, we estimate that 12–15 km of mafic magma was added to the Valle Fértil arc section. Individual mafic additions to the crust take the form of 10–500-m-thick paleohorizontal sills in their emplacement (pretilting) orientation. However, the section is complex along strike, as

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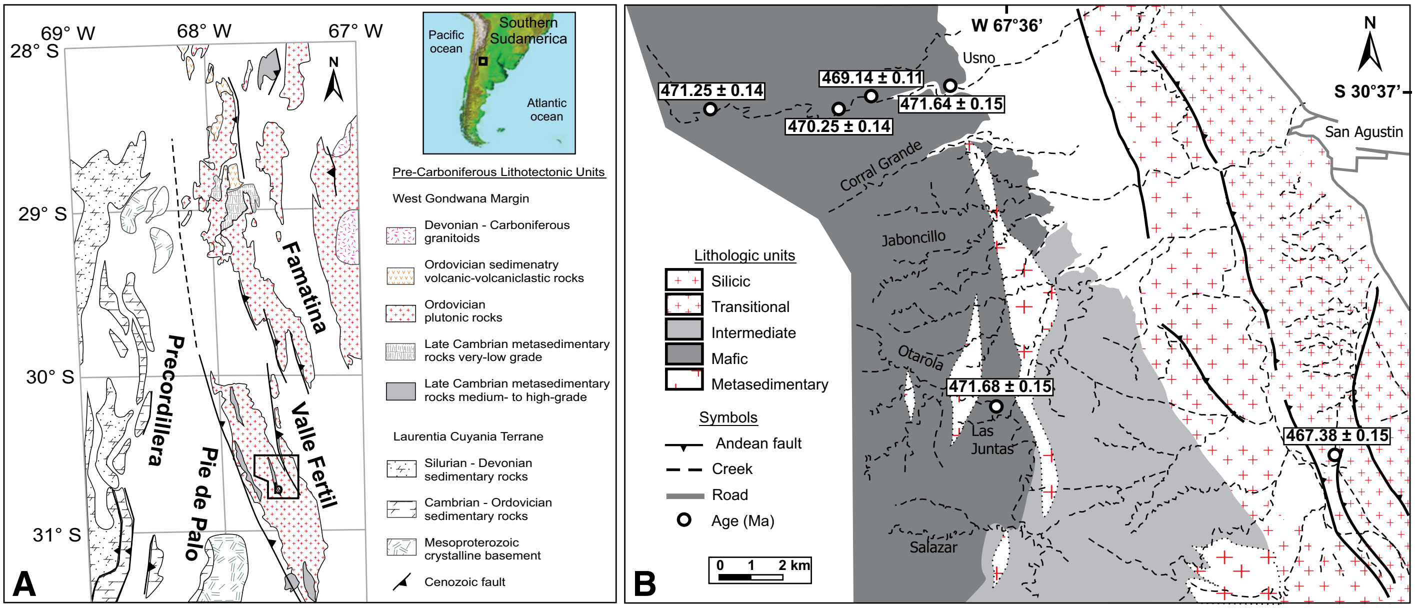

Figure 1. A: Location map of the study area in central South America. The Sierra Valle Fértil and Sierra Famatina ranges (part of the larger Famatinian arc of the western Gondwanan margin) are shown. To the west, across a major tectonic boundary, is the Laurentian Cuyania terrane, which accreted to South America at the end of Famatinian magmatism. B: Simplified map of the central part of the Sierra Valle Fértil range, showing the main geologic units of the Famatinian arc exposed in the study area. The geologic map is a general view of the arc, with the western parts containing the deeper exposures (Pankhurst et al., 1998). Location of the new age-determined samples and the ages are shown in the figure.

more tonalites are found locally in the deeper part of the section in places (Fig. 1). The only country rocks of the Famatinian arc are high-grade (amphibolite and granulite facies) migmatized equivalents of the regionally extensive Puncoviscano Formation (Ducea et al., 2015c), a turbidite sequence of Cambrian–Ordovician age (Pearson et al., 2013) of probable passive margin origin.

Regionally, from Peru to Patagonia, the age distribution of the Famatinian arc ranges between 495 Ma and ca. 466 Ma, but that range only bounds the activity of the arc at the largest scales. Here we report new age data collected from the Sierra Valle Fértil arc section and present a reinterpretation of previously published age data (Ducea et al., 2010).

METHODS AND RESULTS

Field work and sample collection, as well as petrographic and geochemical work complementing this paper, were reported by Tibaldi et al. (2013), Ducea et al. (2015c), and Walker et al. (2015). Six new high-precision U-Pb chemical abrasion–thermal ionization mass spectrometry (CA-TIMS) zircon ages are reported on gabbros and cumulate rocks from the mafic section, including intermediate products, and one upper crustal granodiorite. Analytical techniques and tabulated results are presented in the GSA Data Repository[1].

The new samples were collected from the same general area where previous petrologic studies of the Sierra Valle Fértil were conducted (Otamendi et al., 2009, 2012; Ducea et al., 2010; Walker et al., 2015). Because the Valle Fértil mountain range is a tilted exposure through an arc, our sampling path follows, from west to east, the major igneous units from deeper in the section upward. Therefore, the studied section represents a paleo-vertical sampling transect into the Famatinian arc.

The summary of zircon U-Pb geochronology data, new and previously published, shows a much tighter age range, ~4 m.y. A couple of zircon rim ages of 468.9 Ma and 469.8 Ma (see the Data Repository) are interpreted to be metamorphic ages and are consistent with metamorphic zircon U-Pb ages previously measured (Rapela et al., 2001) (with lesser precision) on metasedimentary rocks from the Famatinian arc. They are within error identical to the magmatic age of the section and demonstrate that metamorphic zircons or zircon rims grow synchronously with high-flux crustal-scale magmatism in middle to deep crustal sections of magmatic arcs.

DISCUSSION

Arc magmatism manifests on both local and plate-scale time scales. Individual volcanic systems can have characteristic life spans from 200 to 300 k.y. to 5–8 m.y. (Ducea et al., 2015a), similar to estimates for chemical differentiation within discrete volcanic centers (Hawkesworth et al., 2000) and plutonic systems (Coleman et al., 2004). However, it has been much more difficult to constrain the characteristic time scales to create entirely new arc crust by those processes. Here we show that the composite age data for the Sierra Valle Fértil imply that the arc section was intruded by voluminous mafic magma that internally differentiated, producing intermediate melts that then interacted with variable amounts of the highly migmatized metapelites and their partial melts to produce heterogeneous tonalities and upper crustal granodiorites on a time scale of only 4 m.y. In addition, the data in Figure 2 show that the process of arc construction was not simply a progressive bottom-up process. For example, the sample yielding the oldest of the CA-TIMS dates occurs near the top of the mafic complex, and continued input to the mafic complex was occurring while the more evolved portions of the arc were being established.

If close to 15 km of the arc thickness is represented by mafic additions from the mantle, that composes about half of the crustal thickness and, given the overwhelming predominance of arc magmatic products in the crust, it also represents 50% of the mass budget of the arc, consistent with geochemical models from here or elsewhere (Ducea et al., 2015b). Most active arcs are ~30–40 km wide and migrate laterally at 2–6 km m.y.^{-1} (Ducea et al., 2015b). Assuming an average lateral migration in the Famatinian arc of 4 km m.y.^{-1} and an instantaneous width of 35 km, the integrated lateral production of mafic magma was 50 km wide over 4 m.y., or a little >12 km m.y.^{-1}. The overall magmatic addition rates (the sum of all magmatic products) are 12 × 30 km = 360 $\text{km}^3\ \text{km}^{-1}\ \text{m.y.}^{-1}$, about half of which is mafic melt. These numbers are similar to the recently reported magmatic addition

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[1] GSA Data Repository item 2017061, analytical techniques and zircon U-Pb ages, is available online at www.geosociety.org/datarepository/2017, or on request from editing@geosociety.org.

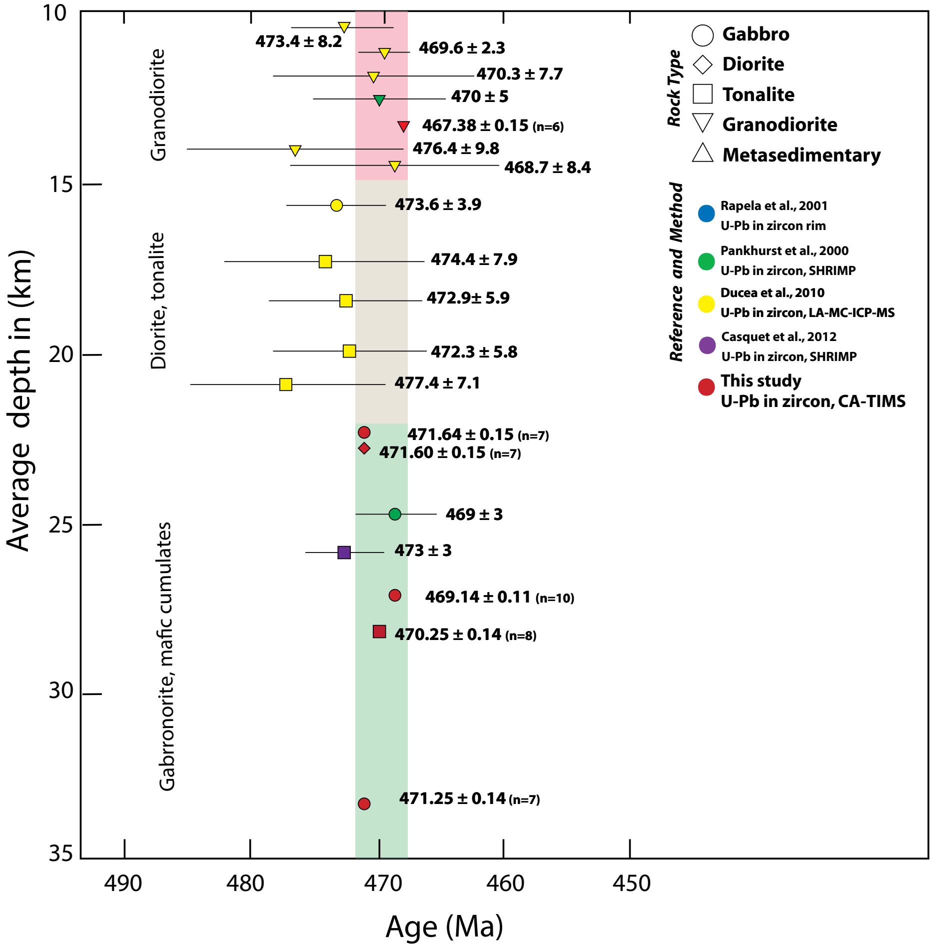

Figure 2. U-Pb ages projected onto an averaged one-dimensional depth section. Because the thickness of the distinct compositional domains is not uniform along the strike of the arc section, it was necessary to create an average thickness and project the data onto that. Relative depths and spacing are preserved, but actual depths will vary for the deepest samples. Vertical colored bar of ~4 m.y. bounds the new high-precision chemical abrasion–thermal ionization mass spectrometry (CA-TIMS) data and overlaps uncertainties in all available data (LA-MC–ICP-MS—laser ablation–multicollector–inductively coupled plasma–mass spectrometry). We take the 4 m.y. range as the duration of igneous activity that formed the arc section. Errors are given at 2σ.

rates for relevant modern and ancient island arcs (Jicha and Jagoutz, 2015), and about an order of magnitude higher than the classic estimates for magmatic addition rates in arcs (Reymer and Schubert, 1984), which are integrated over lifetimes of tens to hundreds of millions of years. The mafic addition rates are comparable to those at slow-spreading mid-ocean ridges and are about half the average addition rates at mid-ocean ridges (Cogné and Humler, 2004).

The total magmatic addition of the Famatinian arc in the Sierra Valle Fértil–Sierra de Famatinia, representing the total amount of magmatic rocks formed during the 472–468 Ma period, includes mafic additions and the recycled preexisting crustal rocks via upper plate partial melting. The total magmatic addition is comparable to the 320 km^3 km^{-1} m.y.$^{-1}$ average oceanic rates (Reymer and Schubert, 1984). If these mafic rates reflect standard mantle melt productivity under thin arcs (oceanic or transitional continental), then the ones determined for thick Andean-type arcs (total magmatic rates between 10 and 150 km^3 km^{-1} m.y.$^{-1}$), half of which is believed to be mafic (Paterson and Ducea, 2015), are much lower even during flare-up periods. This is a fundamental difference between thin and thick arcs that contradicts a common assumption that all arcs are the subject to identical processes of melting in the mantle wedge with similar melt productivities (Grove et al., 2012), or that perhaps melt productivity is proportional to convergence rates.

Ultrahigh magmatic addition rates (300–400 km^3 km^{-1} m.y.$^{-1}$) similar to those described here appear to characterize parts of the continental crust (Coleman et al., 2004) such as the Arabian-Nubian shield (900–600 Ma), the Svekocarelian shield (1900–1700 Ma), or the peri-Gondwanan arc terranes of Europe (700–400 Ma). The causes of their high addition rates have been debated for decades and remain unresolved. We suggest here that those continental crustal segments formed in a manner similar to the case discussed here: high arc migration rates across trenches (either toward or away from the trench) can lead to arc sweeps that result in fast production of new continental crust over larger areas, as we suspect was the case with these classic examples of unusually high magmatic addition rates. Moreover, we suspect that the majority of the continental crust was formed in such arcs over the course of Earth's history (Condie and Kroner, 2013); the average trace elemental budget of the continental crust is consistent with its derivation from thin arcs (e.g., Taylor and McLennan, 1985).

We further propose that the main cause for reducing melt productivity in thick Andean arcs is the crowding effect of cumulate buildup under the arc (DeCelles et al., 2009). Most arcs have a longer lifetime than Sierra Valle Fértil; on average oceanic arcs live ~40 m.y., whereas Andean arcs have an average life of 100 m.y. (Ducea et al., 2015a). In arcs under flare-up mode, or in slowly migrating arcs, the buildup of mafic ultramafic cumulates can rapidly generate enormously thick roots (Ducea and Saleeby, 1998) that crowd the mantle wedge to the point of interrupting normal wedge convection or temporarily stopping it (Ducea et al., 2015a). Thick Cordilleran arcs are probably plagued by this problem for much of their history, excepting times immediately following delamination of the lithosphere.

Arc cumulates are typically pyroxene and amphibole rich (with garnet being an abundant additional phase in continental arcs) and are slightly denser in island arcs to significantly denser in continental arcs (Jull and Kelemen, 2001) than the underlying mantle. Therefore they are removed and recycled into the convective mantle as Raleigh-Taylor instabilities. Long-lived arcs and/or slowly migrating arcs generate mafic and/or ultramafic roots that are much thicker than 30 km (Ducea et al., 2015a). If the Valle Fértil–Famatina addition rates were characteristic for arc magmatism over time, 4–8 times more crust would form over 2–4 b.y. of presumed subduction-like processes and arc magmatism, compared to the present-day volume of continental crust. This is calculated using the modern total length of trenches today (55 × 10^3 km), an average crustal thickness of 30 km in arcs, a 350 km^3 km^{-1} m.y.$^{-1}$ addition rate determined here that yields 8 × 10^8 km^3 of arc crust produced in 2 b.y. compared to 1.5–1.8 × 10^8 km^3, which is the modern volume of continental crust. That excess material is somewhat improperly referred to as crust, because it is dominated by mafic-ultramafic cumulate and restite materials (Jagoutz, 2014). The bulk of the missing crust likely resides today in the mantle as a reservoir of recycled (delaminated) and dispersed nonperidotitic mass, which is distinct from other forms of recycled crust, such as subducted sediment.

ACKNOWLEDGMENTS

Funding was provided to Ducea from the Romanian Executive Agency for Higher Education, Research, Development and Innovation Funding (project PN-II-ID-PCE-2011–3–0217). Funding was provided to Bergantz by U.S. National Science Foundation grants EAR-1049884 and EAR-1447266. We thank Chris Spencer and Brian Jicha for thorough reviews of the manuscript.

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Manuscript received 22 October 2016
Revised manuscript received 23 November 2016
Manuscript accepted 28 November 2016

Printed in USA