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# Upper-Crustal Architecture and Record of Famatinian Arc Activity in the Sierra de Narváez and Sierra de Las Planchadas, NW Argentina

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## Abstract

The 495 to 450 Ma Famatinian orogen, exposed throughout central and northwestern Argentina, formed from east-directed subduction under the Gondwanan margin. The Sierra de Narváez and Sierra de Las Planchadas preserve a rare upper crustal section of the Famatinian arc. New mapping, structural analysis, detrital U-Pb zircon geochronology, as well as major and trace element geochemistry in the Sierra de Narváez – Las Planchadas are presented to give a comprehensive geodynamic portrait of the volcano-sedimentary, igneous, and deformational processes acting within the top of the Famatinian arc in the Ordovician.

Field observations and bulk rock geochemistry agree with previous work indicating that the top of the Famatinian arc consisted of volcanic centers, mafic and felsic feeders, and plutons built into continental crust in a shallow marine arc setting, characterized by fossil-bearing, fine-grained marine sediments interbedded with coarse-grained volcanic-clastic material. Trace element chemistry is consistent with the Sierra de Narváez – Las Planchadas region being a continuation along the main arc axis from the more southerly Sierra de Famatina, not a back arc setting as previously interpreted. Detrital zircon geochronology in Permian and Carboniferous sedimentary units unconformably overlying Ordovician units adds further constraints to the duration of Famatinian arc activity and the source of sedimentary material. Two peaks in detrital zircon ages within Carboniferous and Permian strata at 481 Ma and from 474 – 469 Ma, record periods of enhanced magma addition during Famatinian arc activity. Structural analysis establishes both Famatinian and post-Famatinian (largely Andean) deformation; contractional deformation in the Ordovician, although small relative to middle- to lower-crustal levels of the Famatinian orogen, caused crustal thickening and likely initiated surface uplift. Unlike the Famatinian middle to lower crust, however, where widespread ductile deformation is ubiquitous, shortening here is accommodated by open folding, pressure solution, and likely localized brittle faulting. We briefly speculate on the implications of variable shortening recorded at different crustal levels.

**Keywords:** Famatinian arc; Argentina; upper arc; deformation; flare-up; volcanics

## 1. Introduction

Subduction margins are commonly overlain by magmatic arcs where new continental crust is produced (Rudnick, 1995). In addition to the creation of new crust, arcs are regions of concentrated mineralization, pose potential societal hazards through violent eruptions, and have direct interactions with Earth’s climate and biosphere through crustal thickening, uplift, and erosion, as well as through volatile degassing (Lee et al., 2015; Cao et al., 2016; Ratschbacher et al., 2019). The uppermost regions of an arc are especially important because these relatively thin veneers provide an interface that link tectonically-driven mantle and crustal processes to the biosphere and atmosphere. Whereas studying presently active arcs gives only a single spatial-temporal snapshot, the study of ancient exhumed arcs can offer a more complete spatial and extensive temporal record of geodynamic arc processes active through the lithosphere. However, studies of exhumed arc systems, particularly of the uppermost regions, are often complicated by lack of preservation and exposure.

The Sierras Pampeanas and the southern Puna Plateau, northwestern Argentina, preserve a protracted record of repeated orogenesis and arc activity spanning much of the Phanerozoic. The Ordovician Famatinian orogeny (*ca.* 495 – 450 Ma; Ramos, 1988; Rapela et al., 1998b; Rapela et al. 2018), which followed shortly after the early Cambrian Pampean orogeny (*ca.* 545 – 520 Ma; Rapela et al., 1998a, b; Casquet et al., 2018) resulted from east-dipping subduction along the proto-Gondwanan margin possibly culminating in collision of the Precordillera Terrane (Astini et al., 1995; Thomas and Astini, 1996; Rapela et al., 2018; Weinberg et al., 2018; Otamendi et al., 2020). Remnants of the Famatinian arc, active during the Ordovician Famatinian orogeny, are widely exposed throughout the Sierras Pampeanas and southern Puna Plateau (Figure 1), although as much as 90% of exposure is Ordovician intrusive rocks and mid-crustal rocks, with only sparse volcanic remnants preserved (Ratschbacher et al., 2019).

Despite limited exposure of upper-crustal Famatinian rocks, a significant body of work is devoted to characterizing the uppermost regions of the Famatinian arc (*e.g.*, Harrington and Leanza, 1957; Turner 1967; Maisonave, 1973; Aceñolaza and Toselli, 1977, 1988; Toselli et al., 1990; Cisterna, 1994, 2001; Mángano and Buatois, 1994, 1996, 1997; Aceñolaza et al., 1996; Saavedra et al., 1998; Astini, 2003; Mángano et al., 2003; Fanning et al., 2004; Dahlquist et al., 2008; Cisterna et al., 2010a, b, 2017; Cisterna and Coira, 2014, 2018; Armas et al., 2016, 2018; Coira, 2017). However, several significant issues remain, including questions specific to the Famatinian orogeny and regional arc-tectonics, as well as more generalized arc geodynamic processes. Regional issues, including the timescales of arc activity and construction of the plutonic to volcanic plumbing system, the tectonic context of the preserved volcanic sections in terms of the greater Famatinian system, the nature of the depositional and arc environment in the Ordovician, as well as the extent of upper-crustal deformation during arc activity and mechanisms accommodating this deformation, remain unresolved. Observations of ancient arc systems, like the one presented in this study, can also be used to further develop models for generalized arc processes and structure, including the structural and geochemical nature of an upper-crustal plumbing system linking hypabyssal plutons to volcanic rocks, the interplay between deformation and magmatism/volcanism at upper-crustal levels, and insights into the spatial-temporal evolution of arc systems.

Previous work has resulted in a model of the first-order deformational, stratigraphic, petrologic characteristics of the Famatinian arc and timespans over which these processes operated (Rapela et al., 2018; Weinberg et al., 2018; Otamendi et al., 2020). These studies suggest a dominantly marine arc with both submarine and subaerial volcanic edifices built over a plutonic plumbing system restricted to the interval 463 ± 4 to 486 ± 7 Ma, with a peak of period of magmatic activity between 468 Ma and 472 Ma (Ducea et al., 2017; Rapela et al., 2018). Low energy deep to shallow marine sedimentation was interrupted by high-energy volcaniclastic and volcanic-sedimentary processes proximal to volcanic centers (Cisterna et al., 2010a; Cisterna and Coira, 2014). In total, the Famatinian orogen (*e.g.*, arc and back-arc regions) is suggested to have been shortened by 50% during orogenesis (Christiansen et al., 2019). Here, we present new mapping, geochemistry, and age dating of rocks exposed in the Sierra de Narváez – Las Planchadas to evaluate and refine this model by further characterizing the eruptive, depositional, magmatic, and deformational processes occurring in the upper crust during Famatinian arc activity.

## 2. Geologic background

The Famatinian belt is a subduction-related continental margin orogen, which developed at the southwestern proto-margin of Gondwana during the Early Paleozoic and is presently widely-exposed across northwestern and central Argentina. Elsewhere, this orogen extended discontinuously northward more than 6000 km from latitude *ca.* 39° S to 10° N (Chew et al., 2007; Chernicoff et al., 2010; Ramos, 2018). Flat-slab subduction of the Nazca plate below the South American plate in the central Andes resulted in uplift, exposing deeper levels of the Famatinian belt in the Sierras Pampeanas region (central-northwestern Argentina; Figure 1). Here, the Famatinian Orogen is characterized by a wide (>300 km) Ordovician magmatic belt, that comprises voluminous metaluminous magmatism in the arc zone to the west and predominant peraluminous batholiths in the back arc zone to the east (Pankhurst et al., 2000; Rapela et al., 2018), and extensive high temperature regional metamorphism and ductile deformation at exposed mid-crustal levels (Otamendi et al. 2008; Larrovere et al. 2011, 2020). Exposure of the uppermost regions (*i.e.*, volcanic-sedimentary sequences) of the Famatinian belt in the Sierras Pampeanas are scarce and scattered, limited to areas in the Sierra de Famatina, Sierra de Narváez – Las Planchadas, and Jagüé-Toro Negro (see Rapela et al., 2018 for a review). More extensive exposure of upper-crustal rocks is present in the '*Faja Eruptiva de la Puna Occidental*' (Coira et al., 2009; Pankhurst et al., 2016; Cisterna and Coria, 2017; Weinberg et al., 2018), the northern extension of the Famatinian magmatic arc in the Puna region (northwestern Argentina), where current subduction of the Nazca Plate is at a steeper angle (*i.e.*, not flat slab).

### ***2.1. Upper-crustal stratigraphy and deformation in the Famatinian orogen***

Exposure of the Famatinian upper arc crust in the central and eastern parts of the Sierra de Famatina, and its northward continuation into the Sierra de Narváez – Las Planchadas (Figure 1) is typically characterized by successions of low- to very low-grade metamorphosed marine sedimentary units, volcaniclastic sequences, and volcanic to hypabyssal intrusive bodies. In the sections below, we briefly summarize arc exposure in these two primary areas as well as more limited exposure in the northern Precordillera in Jagüé-Toro Negro.

### 2.1.1. Sierra de Famatina

In the Sierra de Famatina, Ordovician successions exceed 3200 m in total thickness, comprising latest Cambrian to Tremadocian carbonates and siliciclastic rocks (Volcancito Fm.), Floian volcano-sedimentary deposits (Famatina Group) and Middle Ordovician siliciclastic, volcaniclastic and volcanic rocks (Cerro Morado Group, stratigraphic equivalent to the Las Planchadas Fm. in the Sierra de Narváez – Las Planchadas; Astini, 2003; Mángano et al., 2003; Astini and Dávila, 2004). The Ordovician succession stratigraphically overlies Middle – Upper Cambrian Negro Peinado and Achavil Fms., interpreted to have been deposited in a peripheral foreland that developed during the final stages of the Pampean orogeny (Collo et al., 2009). However, the low-grade metamorphism in these older units is thought to be Ordovician in age (Collo et al., 2011). The Negro Peinado Fm. crops out without stratigraphic contact with Lower Paleozoic units, while the Achavil Fm. is unconformably overlain by the Volcancito Fm. (Collo et al., 2011). Astini (2003) recognized five evolutionary stages in the Sierra de Famatina: (1) A late Cambrian to earliest Tremadocian passive margin stage that represents the onset of sedimentation within the Famatina Basin above a previously folded and metamorphosed basement; (2) a late Tremadocian forearc stage characterized by a regional flooding event; (3) an early Floian intra-interarc stage when active volcanism started and the volcanic arc was close to sea level; (4) a late Floian to early Darriwilian volcano-tectonic stage, characterized by a peak in volcanic activity and a regional folding episode, evidenced by an angular unconformity separating the Famatina Group and the Cerro Morado Group (Dávila et al., 2003); and lastly (5) a foreland stage that is interpreted as synorogenic to postorogenic molasse developed after rapid uplift of a thickened orogenic crust (Astini and Dávila, 2004). U-Pb zircon geochronology on rhyolites interbedded with marine sediments of the Cerro Morado group yielded ages of 477 ± 4

Ma (Dahlquist et al., 2008), 470 ± 3 Ma, and 463 ± 2 Ma (Armas et al., 2018). Palinspastic restoration shows a minimum of 2% shortening prior to deposition of the mid-Ordovician Cerro Morado Group (Dávila et al. 2003; Astini and Dávila 2004).

#### *2.1.2. Sierra de Narváez and Sierra de Las Planchadas*

The Sierra de Narváez and Sierra de Las Planchadas Ordovician units consist of Tremadocian and Floian volcanic-sedimentary successions (Mángano et al., 2003; Cisterna and Coria, 2014). Tremadocian rocks, comprising basic and felsic lavas intercalated with sandstones and siltstones, and local graptolitic levels of Lower Tremadocian age, crop out in the Las Angosturas section (NW Sierra de Narváez – Ortega et al., 2005; this study). Cisterna and Mon (2014) document low-grade metamorphism and deformation in these rocks, manifested in cm- to m-scale superimposed folding and development of a discontinuous axial planar cleavage, suggesting NE-SW-oriented shortening. These rocks were subsequently intruded by the Las Angosturas granite at 492 ± 6 Ma (Safipour et al., 2015) to 485 ± 7 Ma (Rubiolo et al., 2002). Floian units (Suri and Las Planchadas Formations) comprise effusive acid to basic lavas, volcaniclastic lithofacies (breccias, sandstones, mudstones, and siltstones), tuffs and volcanogenic sedimentary members (Cisterna and Coria, 2014) rich in marine fauna (brachiopod, trilobites, and conodonts) of Lower-Middle Floian age (Albanessi and Vaccari, 1994; Benedetto, 1994; Vaccari et al., 1994). Existing U-Pb geochronology on rhyolite interbedded with marine sediments of the Suri Fm. yielded an age of 468 ± 3 Ma (Baldo et al., 2003; Fanning et al., 2004). Deformation of these units is evidenced by local m-scale folding with N-S trending axial planes recording a local shortening of 60% (Cisterna and Mon, 2014). Ordovician explosive-effusive arc volcanism took place under subaerial to subaqueous marine conditions (Mángano and Buatois, 1994; Cisterna and Coria, 2014). Voluminous volcaniclastic deposits suggest sediment transport controlled by mass flow processes, given indications of the high rate of sedimentation, strong slope control, and episodes of basin instability (Mángano and Buatois, 1997; Cisterna and Coria, 2014). Ordovician rocks affected by the Famatinian orogeny are unconformably overlain by Carboniferous, Permian, and Paleogene sediments recording primarily subaerial, lacustrine, and fluvial deposition (Turner, 1967; Buatois and Mángano, 1994; Carrapa et al., 2008).

#### *2.1.3. Jagüé-Toro Negro*

Famatinian upper-crustal arc rocks crop out in a third area outside of the Sierras Pampeanas at the northern edge of the Precordillera in Jagüé-Toro Negro (Figure 1). This area exposes Ordovician successions that were grouped in the Chuscho Fm. (Martina and Astini, 2009), comprising a rhythmic succession of greywackes and shales interbedded with basic pillow lavas, subsequently subjected to low-grade metamorphism (Fauqué and Villar, 2003; Martina and Astini, 2009). Pelitic horizons are host to graptolitic fauna of Lower Ordovician age (Ortega et al., 1991). Zircon U-Pb geochronology of pillow lavas yielded an age of 454 – 444 Ma (Fauqué and Villar, 2003).

## 3. Methods

### ***3.1. Field mapping***

An area including the Sierra de Narváez, southern Sierra de Las Planchadas, and intervening valley was mapped at a scale of 1:10,000 over two field seasons. Mapping from individuals and map groups was synthesized, checked with satellite imagery, and drafted in ArcGIS (www.esri.com). The far northwest corner in the high elevations of the Sierra de Las Planchadas and southeast corner in the Sierra de Narváez are only mapped at a reconnaissance-level, with supporting interpretations by high-resolution satellite imagery.

### *3.2. Whole rock major oxide and trace element geochemistry*

Major and trace elements were determined from whole rock samples by X-ray fluorescence (XRF; Table 1) at Pomona College, CA USA. Methods and error analysis were adapted from Johnson et al. (1999). Representative whole-rock powders were prepared in a Rocklabs tungsten carbide head and mill. Powdered sample and flux were mixed in a 2:1 ratio, typically 3.5 g powder to 7.0 g dilithium tetraborate ($Li_2B_4O_7$). The vortexer-blended mixture was fused to a glass bead in a graphite crucible at 1,000° C for 10 min, reground, fused a second time, polished on diamond laps, and analyzed. The Pomona College laboratory analyzes major, minor, and 18 trace elements (Ba, Ce, Cr, Cu, Ga, La, Nb, Ni, Pb, Rb, Sc, Sr, Th, U, V, Y, Zn, Zr) on the same fused bead using a 3.0 kW Panalytical Axios wavelength-dispersive XRF spectrometer equipped with PE, LiF 200, LiF 220, GE, and PX1 industrial crystals. Concentrations are determined using reference calibration curves defined by 55 certified reference materials that span a range of natural igneous, metamorphic, and sedimentary rock compositions (Lackey et al., 2012).

### *3.3. U-Pb zircon geochronology*

Zircon grains were separated from each sample by Yu-Neng Rock and Mineral Separation Services, China. Grains were randomly selected from each separate and mounted in epoxy for cathodoluminescence (CL) imaging. CL images guided analyses, providing a way to avoid analyzing inclusions and mixed core-rim spots where zonation was present. U-Pb geochronology of separated zircons was performed by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) at the Arizona LaserChron Center following the methods described in Gehrels (2000), Gehrels et al. (2006), Gehrels et al. (2008), and Gehrels and Pecha (2014). Standards (SL: 563.2 ± 4.8, Gehrels et al., 2008; R33: 419.3 ± 0.4 Ma, Black et al., 2004; and FC-1: 1099.0 ± 0.6 Ma, Paces and Miller, 1993) were mounted with the unknowns, continually reanalyzed throughout analysis of unknown grains, and were used to correct for fractionation of U, Th and Pb during laser ablation. Standards R33 and FC-1 were also analyzed as secondary standards. Gehrels et al. (2008) compare LA-ICP-MS data collected on the same instrument as our ages to isotope dilution – thermal ionization mass spectrometry (ID-TIMS) ages for samples R33 and FC-1 over two years, which is useful for evaluation of the reproducibility of ages. Standard analyses can be found in Table S1 in the Supplementary Material.

Measurement (*i.e.*, internal) uncertainties were determined for each analysis following Gehrels et al. (2008) and Ludwig (1980) and are reported as standard error of the mean, propagated at one sigma (Table S2). Systematic (*i.e.*, external) uncertainties may be introduced from (1) uncertainty of the published standard age used for fractionation correction; (2) uncertainties in the decay constant of $^{238}$U and $^{235}$U; (3) uncertainties in the initial Pb composition; and (4) average uncertainty of the fractionation correction (standard error between unknowns). Systematic uncertainties are listed for each sample in Table S3.

Zircon ages with discordance higher than 10% were rejected. Analyzed zircon grains with U/Th ratios higher than 12 were removed to avoid grains influenced by metamorphic growth in the range of interest (*i.e.* 500 – 440 Ma, Famatinian orogeny). Only the $^{206}$Pb/$^{238}$U ages are considered for grains with $^{206}$Pb/$^{238}$U ages ≤1.2 Ga; $^{206}$Pb/$^{207}$Pb ages are used for grains that record ages >1.2 Ga. The complete analytical dataset is provided in the Supplementary Material (Table S2).

## 4. Results

### *4.1. Units exposed in the Sierra de Narváez – Las Planchadas*

This area has been the subject of previous studies detailing Ordovician sedimentation and volcanism (Turner, 1967; Mángano and Buatois 1996; 1997; Cisterna et al., 2010a, b; Cisterna and Coira, 2014; Cisterna and Mon, 2014) as well as post-Ordovician history of sedimentation and deformation (Safipour et al., 2015). In this section, we briefly describe exposed units as they pertain to the new mapping and geologic history presented in this study.

#### *4.1.1. Ordovician*

*Suri Formation:* Rocks of the Suri Fm. comprise Lower to Middle Floian interbedded, fine- to coarse-grained sandstones, shales, rare chert, and coarse- to very coarse-grained, moderately-bedded to massive, volcanic-rich sediments (Figure 2c-f). Alteration is widespread, evidenced by epidote-bearing veins and breakdown of biotite and plagioclase grains to chlorite and sericite, respectively. Detailed stratigraphy by Mángano and Buatois (1992, 1994, 1996) subdivides the Suri Fm. into three members differentiated by lithology and interpreted depositional environment: The Vuelta de la Tolas member comprises interbedded fine-grained sediments along with volcanic breccias, conglomerates, and sandstones interpreted to be deposited on a marine slope apron. The Loma del Kilómetro member is made up of fine-grained mudstone, siltstone, and sandstone thought to represent high-gradient shelf deposition dominated by storm and mass flow processes. Lastly, the Punta Pétrea member, which includes coarse-grained volcaniclastic sediments, is interpreted to record deposition in a prograding delta system deposited onto the Loma del Kilómetro member. A detailed account of the stratigraphy is beyond the scope of our study and for the remainder of the manuscript, we refer to three ‘pseudomembers,’ subdivided by volcanic and clastic-sedimentary content, within the Suri Fm., volcanic-rich, volcaniclastic, and fine-grained sediments, roughly analogous to the Punta Pétrea, Loma del Kilómetro, and Vuelta de la Tolas, respectively.

The proportions and grain size of volcanic material incorporated in the Suri Fm. tends to decrease distal to areas with voluminous igneous activity. We document preserved ripples, flute casts, along with brachiopod, gastropod, trilobite, and associated trace fossils, consistent with a shallow marine environment (Figure 2a, b). No exposure of the lower contact of this formation, along with a lack of lateral continuity, prohibit measurement of total unit thickness, but existing stratigraphic sections indicate a minimum thickness of 800 m (Cisterna and Coira, 2014).

*Tremadocian metasediments:* In the Sierra de Nárvaez, rocks lithologically similar to the Suri Fm. crop out (Cisterna et al., 2010b). However, we differentiate these rocks from those of the Suri Fm. based on lack of continuity across major thrust faults and intrusive timing relationships which suggest Tremadocian metasediments may be older than rocks of the Suri Fm. (addressed below).

*Narváez Granitoid:* The Narváez Granitoid is a medium-grained to porphyritic, K-feldspar granite (also referred to as the Las Angosturas granite, which crops out as a large body in the Sierra de Narváez) that is commonly greenish in color due to extensive oxidation, epidotization, and retrogression of biotite to chlorite (Figure 1, 3a). Mafic enclaves are common but are not volumetrically significant in comparison to the proportion of granitoid material (Figure 3a). In the northern map area, granitoids are characterized by a hypabyssal porphyritic texture indicative of sub-volcanic origin (Figure 3a). K-feldspars reach up to 5 cm and variably exhibit complex zonation with rapakivi texture. Clear cross-cutting intrusive relationships are observed in the northern part of the map area, where the Narváez granite intrudes steeply-dipping sedimentary and volcaniclastic successions of the Tremadocian metasediments. At contacts with sedimentary units, cm-scale thick chilled margins with finer grain-sizes are observed. The Narváez granitoid has a U-Pb zircon age of 485 ± 7 Ma (Rubiolo et al., 2002) and 492 ± 6 Ma (Safipour et al., 2015).

*Las Planchadas Formation:* The Las Planchadas Formation consists of Lower – Middle Floian fine-grained volcanic and porphyritic rock, including lava flow and hypabyssal intrusive rhyolite, dacite, and basalt as well as local welded rhyolite tuff. Rhyolite lava is pink to pink-grey, commonly includes mm-scale quartz phenocrysts and lithic fragments, and preserves lithophysae, interpreted to have formed during devolatilization of the lavas (Figure 3b, d). Both bedding-parallel (subaerial or sill intrusion) and discordant (intrusive) relationships relative to host strata are recorded (Figure 3e, f). Rhyolite bodies range in size (m- to 100 m-scale) and texture. Grey-colored dacite commonly includes mm-scale quartz phenocrysts and crops out as isolated bodies, mostly in the southern portion of the Sierra de Las Planchadas. Dark basalts, many of which are thin (<2 m) dikes and less commonly 10 m-scale bodies that exhibit columnar jointing, weather to reddish-black and include plagioclase ± pyroxene phenocrysts. A U-Pb

SHRIMP age of 468.3 ± 3.4 Ma was calculated from a porphyritic rhyolite (Fanning et al., 2004).

### *4.1.2. Carboniferous*

*Agua Colorada Formation:* Unconformably overlying the Ordovician rocks, the Carboniferous Agua Colorada Fm. consists of medium- to coarse-grained arkose to quartz sandstone, finely-bedded shale, and bedded sandstone with burrows (Turner, 1967). Sandstone and shale layers are interbedded with pebble-sized clast-supported conglomerate. Pebble- to boulder-sized blocks of Ordovician volcanic rocks and hypabyssal granitoids are commonly incorporated in the lowermost sections. The unit has been previously interpreted to record sedimentation in a large, deep, open lake (Buatois and Mángano, 1994). A unit thickness of approximately 200 m measured by Safipour et al. (2015) is consistent with our new mapping.

### *4.1.3. Permian*

*De La Cuesta Formation:* The De La Cuesta Formation comprises dark red, medium- to coarse-grained arkose to quartz sandstone with m-scale aeolian cross-stratification and rare shale layers that conformably overly the Carboniferous strata. Sandstone strata contain rare cm-scale, green pyrite oxidation rings and more common leaching spots. Rare detrital biotite indicates a relatively short source-to-deposition distance. Sandstone strata are capped by ~100 m of laminated lacustrine fine-grained sandstone, siltstone, mudstone, and shale. A total thickness of approximately 1000m measured by Safipour et al. (2015) is consistent with our mapping.

#### 4.1.4. Paleogene

*Tambería and Guanchín Formations:* Upper Miocene rocks of the Tambería and Guanchín Formations consist of poorly-consolidated fluvial sandstone and channel conglomerates, interbedded with laminated lacustrine silts and clays as well as tuff layers (Carrapa et al., 2008). An overall thickness of approximately 2500 m was previously measured by Safipour et al. (2015); however, only the lower members of this unit crop out within the map area and we therefore cannot confirm the full unit thickness

#### 4.1.5. Quaternary

Fan, terrace, ephemeral and active stream deposits, and evaporites are present throughout the map area but are not differentiated. Although recent mass wasting is common, we only differentiate one large, map-scale slide block (Qls – Figure 4). Structures within this slide block are largely preserved, but the clear head scarp and lateral slide faults indicate the block is not in place.

### 4.2. Geological description of the Sierra de Narváez – Las Planchadas

We subdivide the area into three regions that are differentiated based on the age and structure of exposed rocks (Figure 4): to the west in the Sierra de Las Planchadas, Ordovician metasediments are intruded by numerous Ordovician dikes, sills, and plugs of basaltic, dacitic, and rhyolitic compositions. To the east, the Sierra de Narváez is dominated by an expansive Ordovician hypabyssal body (Narváez Granitoid), which is unconformably overlain by Permo-Carboniferous and Tertiary strata. In the central region, separated from the eastern and western regions by laterally-continuous, N-S striking thrust faults, a sequence of Ordovician to Permian sedimentary strata are folded and faulted; these rocks are largely unconformably overlain by Quaternary cover (Figure 4, 5).

The western region is characterized by Ordovician metasedimentary rocks of the Suri Fm. interbedded with and intruded by voluminous volcanic and hypabyssal rocks of the Las Planchadas Fm. Here, metasediments of the Suri Fm. are compositionally variable; thick (up to *ca.* 5 m), coarse-grained, massive to poorly bedded strata with chiefly comprising reworked volcanic material consistent with high-energy deposition (e.g. volcaniclastic debris flows and turbidity currents; Figure 2e) laterally transgress to fossil-bearing siltstone and laminated mudstone (Figure 2c, d), the latter indicating low-energy, shallow marine deposition (Mángano and Buatois 1992, 1994, 1996; Cisterna and Mon, 2014; Cisterna and Coira, 2014; Cisterna et al., 2017). In general, Suri Fm. in the west and central Sierra de Las Planchadas include large proportions of volcaniclastic material, which grades into a higher proportion of finer-grained, bedded rocks in the east. In this area, rocks of the Suri Fm. are intruded by three compositionally-distinct igneous facies. Dacites immediately south of the Sierra de Las Planchadas show a porphyritic texture with quartz and feldspar phenocrysts in a fine-grained groundmass, consistent with moderately fast cooling in a hypabyssal or subaerial environment. Fine-grained granitic intrusive bodies are concentrated in two clusters within the Sierra de Las Planchadas, both of which are approximately centered on regions of intensely flow-banded and folded rhyolite (Figure 4). The southern flow-banded region (27° 46.05’S, 68° 4.66’W) crops out as two distinct bodies separated by a fault of unknown displacement; both bodies have an equant outcrop pattern and are ~1km in diameter. The more northerly region (27° 43.91’S, 68° 5.03’W) is elliptical with a long axis of ~3km and a short axis of ~2km. Massive to weakly-banded rhyolite-dacite bodies intrude parallel and discordantly into volcaniclastic strata; these bodies tend to decrease in abundance and volume away from the regions of intense flow banding. In addition to abundant rhyolite-dacite volcanic facies, medium-grained plutonic bodies crop out on the eastern flank of the Sierra de Las Planchadas. We refer to these rocks as the Las Planchadas Granitoid in Figure 4.

The eastern region is dominated by a body of Narváez Granitoid (*i.e.* Las Angosturas pluton) that exceeds 50 $km^2$. An irregular intrusive contact with the Tremadocian metasediments, similar in lithology to the Suri Fm., but clearly older than the Narvaéz granitoid (492 ± 6 – 485 ± 7 Ma; Safipour et al., 2015; Rubiolo et al., 2002) and therefore also older than the Suri Fm., is exposed on the western flank of the Sierra de Narváez. The southern and eastern extents of pluton exposure are unconformably overlain by Carboniferous and younger strata. This sequence of Carboniferous to Permian strata, including the Agua Colorada Fm. and De La Cuesta Fm., are thrust-duplicated and unconformably overlain by the Neogene Tambería Fm. and Guanchín Fm. (Figure 4, 5). A suite of granitic dikes that intruded into Narváez Granitoid and Tremadocian metasediments cluster on the west side of the Sierra de Narváez. These dikes tend to have long axes that trend ~NW-SE, approximately perpendicular to the voluminous rhyolitic to dacitic igneous bodies exposed to the east in the Sierra de Las Planchadas.

The central region is bound by two major thrust faults, the east-dipping Narváez thrust to the east and the west-dipping Las Planchadas thrust to the west. Both faults place Ordovician rocks over Permo-Carboniferous strata. Within this region, south plunging open folds are cut by bivergent thrust faults, duplicating the pre-Tertiary stratigraphy (Figure 4, 5). To the south, the central region thins and is covered by Quarternary sediments as the Narváez and Las Planchadas Thrusts converge.

### *4.3. Structure of the Sierra de Narváez – Las Planchadas*

#### *4.3.1. Folding*

Rocks of the Suri Fm. are affected by open, upright, gently S-plunging folds ($F_1$) with variable wavelengths that fold bedding ($S_0$) and in some rock types are associated with a penetrative axial planar cleavage ($S_1$) striking ~NNE-SSW. The orientation of the best-fit axial plane, determined from bedding orientations, is 193/75 (using the right-hand rule convention; Figure 7a), whereas the mean axial planar cleavage ($S_1$) is 026/84 (Figure 7c, 8). The reader should note the difference in orientation between the best-fit axial planes and the best-fit axial planar cleavage. We interpret this difference to indicate overprinting of Ordovician folds by post-Ordovician folding, which we discuss in more detail below. In outcrop, cleavage spacing varies from sub-cm- to m-scale, dependent on local rock composition and grain size (Figure 8a). It is moderately- to strongly-developed in the Suri Fm. but no appreciable cleavage is observed within intrusive rocks of the Las Planchadas Fm. At the microscale, abundant dissolution seams indicate the cleavage formed primarily by solution-reprecipitation processes (*e.g.*, pressure solution; Figure 8b).

A dominant structure expressed in the Suri and Las Planchadas Fms. is the *Vuelta de Las Tolas* anticline, which can be traced from the central Sierra de Las Planchadas to south of the Río Chaschuil (Figure 4, 6a Mángano and Buatois, 1996, 1997; Cisterna et al., 2017). Because of the open fold geometry and strongly developed axial planar cleavage, we ascribe the *Vuelta de Las*

*Tolas* anticline to have initially formed during $F_1$. Hypabyssal bodies of the Las Planchadas Fm. commonly record discordant relationships with outcrop-scale folds within the Suri Fm., and magmatic mullion structures are present along rhyolite plug margins, with mullion axes subparallel to larger-scale fold orientations (Figure 6b, c). Based on similar orientation and geometry, we relate mullion structures to $F_1$. We measured the local elongation related to $F_1$ folds (*i.e.*, those recording an axial planar cleavage - Figure 6a, or magma mullions - Figure 6b, c) following $e = \frac{\ell - \ell_0}{\ell_0}$ where $e$ is the elongation (a negative value for contraction), $\ell$ is the current length, and $\ell_0$ is the original length. We calculate $e$ = -0.1 – -0.15, or 10 – 15% shortening in these rocks. In part because of volume loss during dissolution, we are unable to provide a robust estimate of total shortening at the microscale (*e.g.*, Figure 8b).

Carboniferous and Permian rocks of the Agua Colorada Fm. and De La Cuesta Fm. also record km-scale, upright to inclined S-plunging folds (best-fit axial plane orientation of 014/88; Figure 7b), but folding in these younger rocks approaches close fold geometries (Figure 5) and they lack any penetrative axial planar cleavage. Although no clear evidence of fold superposition was identified in the field, the difference in fold geometries, orientations, and associated axial planar cleavage between the Ordovician Carboniferous and Permian rocks supports at least two episodes of folding, making that recorded in the Carboniferous and Permian rocks $F_2$. We further address timing and geometric relationships between $F_1$ and $F_2$, including comparison to previous work, in the discussion below.

### *4.3.2. Faulting*

Rocks of the Sierra de Narváez – Las Planchadas are cut by numerous, dominantly N-S striking faults (Figure 4). These structures tend to dip moderately to the west in the Sierra de Las Planchadas and moderately to the east in the Sierra de Narváez, primarily recording reverse-sense kinematics (evidenced by normal drag features and older-on-younger age relationships) in both regions. Two of these faults, the Las Planchadas thrust and Narváez thrust are laterally continuous over distances >10 km, and place Ordovician rocks of the Suri Fm., Las Planchadas Fm., and Narváez Granitoid over the younger cover sequence (Figure 4). Based on our interpretation of subsurface structure, the long laterally continuous faults commonly have displacements >100m (Figure 5). Faults expressed only within the Suri Fm. in the Sierra de Las Planchadas tend to be more closely spaced (<1 km) with minor displacements (on the order of 10 m) and shorter lateral extents relative those exposed within the cover sequence (Figure 4). Additional structures with normal-sense or ambiguous kinematics are locally present but their relation to contractional structures is unclear; some normal faults may record scarps of large-scale mass wasting. We identified a large (~3 x 2 km) block defined by a normal fault contact with surrounding rocks that we interpret to be a slide block (Qls in Figure 4). The block comprises largely-undisturbed Agua Colorada Fm. and Tremadocian metasediments which have been offset by ~100 m relative to the in-place rocks to the east.

### *4.3.3. Magmatic and sub-magmatic deformation*

Rhyolites and dacites of the Las Planchadas Fm. commonly record strong differentiated layering ($S_{mag}$) which we interpret to be magmatic flow banding. $S_{mag}$ is commonly folded into a tight to isoclinal folds and in some instances record boudinage (Figure 3b, c). At the micro-scale, flow banding is characterized by a differentiated fabric that is relatively isotropic at the grain scale, further supporting that deformation occurred in the magmatic or sub-magmatic state (Figure 9a). Flow banded rocks do not record any consistent pattern in fold orientation, sense of shear, or in the orientation of rare lineations developed on the banded surface ($S_{mag}$). Flow banding, folding, and boudinage all indicate high strain that is a result of magmatic flow and not later tectonic processes.

## ***4.4. Petrography and Geochemistry***

We preformed bulk rock major and trace element geochemistry on 14 samples from the Suri Fm., Las Planchadas Fm., and Narváez Granitoid (Table 1). Sample locations are plotted on Figure 4. In the section below, we provide brief petrographic descriptions and sample analytical results.

### *4.4.1. Petrography*

Outcrop and thin section observations indicate Ordovician rocks in the Sierra de Narváez – Las Planchadas region have undergone extensive alteration. The glassy matrix of the volcanic rocks is typically devitrified to chalcedony (Figure 9a). Banded rhyolite flows (sample B17; Figure 9a) and welded tuff, which contain a few percent phenocrysts of quartz, sanidine, and/or plagioclase, record complete devitrification into a fine-grained, red, green, or dark groundmass (*e.g.*, samples B14, B17, E39B, E56; Figure 9a-d). Reaction of plagioclase to sericite is common; the extent of sericitization ranges from complete in some grains to other grains where it is restricted to certain growth zones, presumably those with a higher anorthite content (*e.g.*, C31B basalt with altered cores). Where present, biotite phenocrysts have altered to Fe-rich chlorite (blue interference colors; *e.g.*, C16; Figure 9e). Additionally, basaltic rocks have altered pyroxenes (*e.g.*, C31B). Some highly-altered rocks contain vesicles that are filled with calcite and epidote (*e.g.*, samples B17, E37A). Lithophysae in the banded rhyolite flows are mostly recrystallized to quartz (Figure 9a), but generally maintain the primary lithophysae structure.

Despite widespread retrogression, euhedral phenocrysts of quartz, sanidine and plagioclase (1-5 mm in size), still preserve magmatic features (Figure 9). Sanidine and quartz show evidence of resorption with embayed grain boundaries in most rhyolite and dacite samples (*e.g.*, quartz in C42; sanidine in B58; Figure 9b). Sample C16 shows a smaller population of quartz with resorbed margins while the slightly larger grains are not affected by resorption. In most samples, plagioclase is euhedral and characteristic of albite twinning; only rarely (*e.g.*, C16 basalt) does it show sieved textures in cores. Some basalts (*e.g.*, E37A) show a bimodal distribution of dominantly smaller plagioclase laths and fewer larger grains. In several samples, the three minerals are clumped into glomerocrysts (*e.g.*, A52, B58; Figure 9c). Several samples contain phenocrysts, phenocryst fragments, and lithic fragments, including basalt, devitrified fiamme, and glass shards (E56; Figure 9d). Based on textures and depositional structures at the outcrop scale, these samples are interpreted to be a welded tuff (E56) and a lahar deposit (C50).

The Narváez Granitoid intrusion is fine- to medium-grained and has granophyric texture. Quartz grains commonly record sweeping undulose extinction. In sample A60, the granophyre includes small, parallel fractures that are filled with quartz (Figure 9f).

### *4.4.2. Geochemistry*

#### *4.4.2.1. Hypabyssal Narváez Granitoid*

Two samples of the hypabyssal Narváez Granitoid from the Las Angosturas pluton in the Sierra de Narváez record $SiO_2$ contents of ~68 and 73 wt. %, ~0.4 wt. % $TiO_2$, 3 and 3.7 wt. % $FeO^t$, 0.7 and 1.6 wt. % CaO, and ~7 wt. % $Na_2O$ + $K_2O$ (Table 1). On a total alkali vs. silica classification diagram, compositions plot in the granite field (Figure 10a). The samples have aluminum saturation index (ASI) values of ~1.2 (*i.e.*, peraluminous) and are scattered on a $K_2O$ vs. $SiO_2$ diagram, both in the low-K and high-K field, suggesting post-crystallization alteration (Figure 10b). They show variations in Rb (13 and 109 ppm) and Ba (69 and 630 ppm), low contents of Sr (≤ 124 ppm), Nb (≤ 11 ppm) and Zr (≤ 148 ppm) (Table 1), and relatively high values of Y (37 and 44 ppm). The REE patterns show a $La_N/Yb_N$ ratio of about 6 and a negative Eu anomaly ($Eu_N/Eu^*_N \sim 0.5$) (Figure 10c).

#### *4.4.2.2. Volcanic mafic rocks*

Four samples of mafic dikes from the Sierra de Las Planchadas show relatively low contents of $SiO_2$ (50 to 54 wt. %), $TiO_2$ (0.7 to 1.2 wt. %), $FeO^t$ (7.8 to 8.9 wt. %), alkalis (3.6 to 5.6 wt. %), but scattered CaO (5.7 to 10 wt. %) (Table 1). On a total alkali vs. silica classification diagram, the compositions plot close to the border between basalt/basaltic andesite and trachybasalt/basaltic trachyandesite (Figure 10d); in the Winchester and Floyd (1977) classification scheme, based on the ratios of immobile elements $Zr/TiO_2$ vs. Nb/Y (Figure 10e), the mafic rocks cluster in the andesite/basalt field. This suggests these rocks underwent post-crystallization chemical modification, which is also indicated by the $K_2O$ vs. $SiO_2$ diagram with samples plotting across low-K to high-K fields (Figure 10b). The ASI values range between 0.58

and 0.8 classifying the basaltic samples as metaluminous. Samples show low contents of Rb (≤ 22 ppm with exception of an anomalous value of 72 ppm), Ba (≤ 246 ppm), Sr (≤ 335 ppm), Nb (≤ 7 ppm), Zr (≤ 77 ppm) and Y (≤ 25 ppm). Two samples of basalt show REE patterns with a $La_N/Yb_N$ ratio of ~3 and a slightly negative Eu anomaly ($Eu_N/Eu^*_N$ ~ 0.9) (Figure 10c).

#### *4.4.2.3. Volcanic felsic rocks*

Six samples of felsic rocks, three from lava flows and three from intrusive plugs, show a wide range in the content of $SiO_2$ (68 to 81 wt. %) and $FeO^t$ (0.8 to 3.6 wt. %) but restricted contents of $TiO_2$ (0.1 to 0.5 wt. %), CaO (0.1 to 1.7 wt. %), and moderate contents of alkalis (6.1 to 8.2 wt. %) (Table 1). On the total alkali vs. silica classification diagram, compositions plot mostly in the rhyolite field with exception of one sample classified as a dacite (Figure 10d). In the $Zr/TiO_2$ vs. Nb/Y (Figure 10e), these rocks mostly classify as dacite and rhyolite. ASI values range between 1.04 and 1.19 (*i.e.*, slightly peraluminous to peraluminous, plausibly influenced by the devitrification of the glassy groundmass in the rhyolite flows). They have a wide range in the contents of Rb (26 to 156 ppm), Ba (198 to 852 ppm), Sr (13 to 244 ppm), Nb (7 to 25 ppm), Zr (113 to 207 ppm) and Y (24 to 58 ppm). Two samples show REE patterns with $La_N/Yb_N$ ratios of 2.5 and 8.8, and a negative Eu anomaly ($Eu_N/Eu^*_N$ ~ 0.5) (Figure 10c).

#### *4.4.2.4. Volcaniclastic rocks*

Two samples record $SiO_2$ contents of ~ 48 and 57 wt. %, $TiO_2$ of ~0.7 wt. %, $FeO^t$ of 6.5 and 9.4 wt. %, CaO of ~9 wt. %, and $Na_2O + K_2O$ of 4.1 and 8.2 wt. % (Table 1). In the total alkali vs. silica classification diagram, one sample plots at the boundary between basalt and trachybasalt, while the other is within the trachyandesite field (Figure 10d); classified as $Zr/TiO_2$ vs. Nb/Y, one sample plots in the andesite/basalt field and the other as a subalkaline basalt (Figure 10e). The samples have ASI values of 0.52 and 0.86 (*i.e.,* metaluminous). They contain 61 and 75 ppm Rb, 116 and 292 ppm Ba, 84 and 206 ppm Sr, 11 and 19 ppm Y, and low Nb ($\leq$ 5 ppm) and Zr ($\leq$ 63 ppm) (Table 1). The basalt sample has a flat REE pattern ($La_N/Yb_N = 3$) and no Eu anomaly ($Eu_N/Eu^*_N = 1$; Figure 10c).

### *4.5. U-Pb zircon geochronology*

We dated five samples of Carboniferous and Permian strata (Agua Colorada and De La Cuesta Fms., respectively) from the study area by means of LA-ICP-MS U-Pb detrital zircon geochronology (See Figure 4 for sample locations). Our use detrital of zircon geochronology on Late Paleozoic strata overlying Ordovician arc rocks aims to document the full range of Ordovician magmatic activity in the study area. Although the youngest Famatinian magmatic activity, which some authors suggest is as recent as 440 Ma (Bahlburg et al., 2016), could have been eroded from the upper levels of the arc column in the study area, it would likely still be recorded in the overlying Late Paleozoic units. Geochronology results are plotted in Figure 11; full age spectra are plotted in the left column and restricted age ranges are plotted in the right column to show spectra detail. Unprocessed data are tabulated in Table SM 1. Individual sample results are summarized below:

Sample BR32-2 (Sandstone, De La Cuesta Fm.). Ages range from 3327 – 299 Ma (n = 76/98). Dominant age-peaks occur at 558 and 1038 Ma (Figure 11 a, b). Several minor are populations are present at *ca.* 300, 384, 470, 524, 1374, 1750, and 2790 Ma.

Sample A24 (Siltstone, Agua Colorada Fm.). Ages range from 496 – 305 Ma (n = 44/87). The distribution of ages (Figure 11 c) records two well-defined peaks at 308 and 481 Ma.

Sample E26 (Sandstone conglomerate, Agua Colorada Fm.). The range of ages is 2093 – 346 Ma (n = 72/91). Dominant age peaks are at 474, 525 and 586 Ma (Figure 11 d, e). Subordinate peaks are present at *ca.* 910, 1075, and 1224, as well as individual zircon ages ranging between 2200 – 1700 Ma.

Sample E32-2 (Sandstone, Agua Colorada Fm.). Ages range from 2448 – 338 Ma (n = 69/99). Ages record a single dominant peak at 469 Ma, along with two minor peaks at *ca*. 1017 and 338 Ma and scattered older ages (Figure 11 f, g).

Sample A78 (Sandstone, Agua Colorada Fm.) Ages range from 1000 – 448 Ma (n = 19/26), with a dominant peak at 472 Ma, and individual ages between *ca.* 1000 – 500 Ma (Figure 11 h, i). Although the number of analyzed grains in this sample is not sufficient for a representative characterization of the entire detrital population, we include it to document a maximum age and the timing of Famatinian arc activity.

## 5. Discussion

### *5.1. Architecture of an upper-crustal arc plumbing system*

Ordovician rocks in the Sierra de Las Planchadas comprise Tremadocian to Dapingian volcanic-sedimentary successions (468 ± 3.4 Ma rhyolite of the Las Planchandas Fm., Fanning et al., 2004) and relatively older hypabyssal granitoids in the Sierra de Narváez at 492 ± 6 Ma (Las

Angosturas granite, Safipour et al., 2015), 485 ± 7 (Las Angosturas granite, Rubiolo et al., 2002). The most extensive deposits are the Floian-Dapingian successions (Suri Fm. and Las Planchadas Fm.) in the Las Planchadas area (Figure 4). These Ordovician rocks have been hydrothermally altered, so geochemical data presented here are only used for first-order interpretations. The granites and rhyolites in the Sierra de Las Planchadas are similar in composition and it is possible that either the pluton directly fed the rhyolite lavas and plugs, or the pluton and rhyolites are sourced from the same connected magma plumbing system (Figure 12). The REE patterns of rhyolite and granite in the Sierra de Narváez – Las Planchadas are similar to those of rhyolite and the Ñuñorco granite in the Sierra de Famatina (Figure 10c; Dahlquist et al., 2008), suggesting that the present study area may be a northerly extension of the main arc exposed in the Sierras Pampeanas.

The tectonic setting of the Sierra de Narváez – Las Planchadas region during the Ordovician remains controversial. Some authors suggest a back-arc setting (Mannheim, 1993; Clemens, 1993; Toselli et al., 1996; Cisterna et al., 2017) while others, a monoclinic tensional or transtensional intra-arc basin within the main arc (Mangano and Buatois, 1996; Cisterna et al., 2010a). More recently, Cisterna et al. (2017) suggest that during the Tremadocian, volcanism in the region was related to the evolution of a marginal basin through an extensional regime above an eastward-dipping subducting slab, but Floian-Dapingian magmatism is related to a volcanic arc-back-arc basin system, which evolved on attenuated continental crust. However, Th/Yb vs. Ta/Yb ratios (plot of Pearce, 1982) of basalt samples belonging to the Floian-Dapingian successions provide an immobile element method of identifying volcanic series, typical of calc-alkaline signatures. Moreover, the Floian-Dapingian calc-alkaline basalts mostly overlap with calc-alkaline mafic rocks of the *ca.* 470 Ma *Faja Eruptiva de la Puna Occidental* (22°S–26°S; Coira et al., 2009) and the main arc from the Sierras Pampeanas (27°S–32°S; see compiled data from Alasino et al., 2016), while they differ from older mafic rocks consisting of *ca.* 485 Ma tholeiitic to calc-alkaline affinities (Alasino et al., 2016) (Figure 10f). This supports not only common petrogenetic processes in the whole magmatic column but also that the Floian-Dapingian volcanic rocks in the studied region are part of the main arc.

### 5.2. Structural evolution of the Sierra de Narváez – Las Planchadas

Rocks in the Sierra de Narváez – Las Planchadas record a protracted, polyphase deformational history spanning the Ordovician through to present day Andean structures. The dominant structures record ~E-W (present day orientation) contractional folding and faulting during the Famatinian and Andean orogenies. Although evidence supporting contractional deformation is ubiquitous, ascribing specific structural elements or trends to either Famatinian or Andean orogenies, both of which include a principal component of ~E-W (present day orientation) contraction, is not trivial. Intrusive relationships of the Las Planchadas Fm. and Suri Fm. indicate deformation synchronous with early to middle Ordovician magmatism (468 ± 3.4 Ma age for rhyolite from the Las Planchandas Fm., Fanning et al., 2004). Although folds within both Ordovician ($F_1$) and younger cover units ($F_2$) have similar orientations (Figure 7a, b), likely due to similar orogenic forcings, the more open geometries, increased scatter, and asymmetry of $F_1$ (Figure 7a) could indicate E-W contraction in the Ordovician that was refolded during $F_2$ Andean deformation. An early (Ordovician) phase of contraction is supported by the penetrative solution-reprecipitation axial planar cleavage which is absent in younger rocks. However, the orientation of the axial planar cleavage in Ordovician rocks is not parallel to the orientation of the axial plane in neither Ordovician nor younger rocks (Figure 7). This discrepancy is consistent with Ordovician fold orientations that have been overprinted or otherwise disturbed by younger folding.

Pre- to syn-intrusive Ordovician shortening is further supported by previous observations. For example, Turner (1967) described diabase dikes that cut folded Suri Fm. but are not themselves affected by folding and do not intrude the overlying Agua Colorada Fm. and Las Planchadas Fm. These observations are consistent with a pre-dike folding event ($F_1$). Turner (1967) also noted an angular unconformable contact between the folded Ordovician Suri Fm. and the overlying Carboniferous Agua Colorada Fm. Lastly, Cisterna and Mon (2014) document rare outcrops of in the NW Sierra de Narváez that record two superimposed folding phases at the cm- to m-scale in Tremadocian medasediments, then later intruded by the Narváez granitoid. They suggest a genetic relationship between the second episode of folds recorded in the Tremadocian units and the folding episode documented in the Suri. Fm. ($F_1$).

In agreement with Cisterna and Mon (2014), arc deformation documented in this study may be linked to the intra-Ordovician orogenic episodes (Tumbaya and Guandacol phases, in the Early Ordovician and Early – Middle Ordovician, respectively) documented at upper-crustal levels throughout the Famatinian belt (Salfity et al., 1984; Moya, 1999, 2015; Astini and Dávila, 2004; Kirschbaum et al., 2006; Hongn and Vaccari, 2008). Particularly, deformation recorded in the Suri Fm. in the Sierra de Narváez – Las Planchadas is temporally and spatially correlated with the regional folding episode of the early Ordovician Famatina group recorded in the nearby Sierra de Famatina (Dávila et al., 2003; Astini and Dávila, 2004). Much of the thrust faulting is constrained to post-Permian and even post-Tertiary on the east side of the Sierra de Narváez, based on incorporation of the De La Cuesta Fm. and Tambería and Guanchín Fms., respectively (Figure 4, 5). Because of the similarity in interpreted shortening direction between the Famatinian and Andean orogenies, we lack evidence to ascribe any of the faulting, even within the Suri Fm., to the Ordovician.

Lastly, contraction in the Ordovician further supports the Sierra de Narváez – Las Planchadas region as a northern continuation of the main Famatinian arc. Documented deformation is consistent with main arc contraction and does not fit the traditional view of extension in a back-arc setting. Ordovician contraction in the Sierra de Narváez – Las Planchadas may record the first stages of surface uplift, correlative with rapid exhumation of Ordovician plutonic rocks documented in the Sierra de Famatina (Astini et al., 2003; Astini and Dávila, 2004; Dahlquist et al., 2008). However, unlike the Sierra de Famatina, we found no evidence of basin deposition at this time in the Sierra de Narváez – Las Planchadas.

### *5.3. Comparing upper- and mid-crustal deformation in the Famatinian Orogen*

Estimates of regional shortening calculated by cross-section restoration in the Sierra de Famatina (minimum of 2%; Astini and Dávila, 2004) and the open fold geometries characteristic of Ordovician deformation in the Sierra de Narváez – Las Planchadas (Figure 5, 6a) suggest a lack of extensive shortening at these exposed upper-crustal levels (unless shortening occurred along discrete faults not exposed or obfuscated by later deformation). In the Sierra de Narváez – Las Planchadas, our shortening estimates from restoring open folds with an associated axial planar cleavage (interpreted to be related to Famatinian deformation due to the presence of an axial planar cleavage; Figure 6a) and magma mullions (Figure 6b, c) range from 10 – 15%. Note, however, that this is a maximum estimate from folding, because rocks could have been further contracted by post-Ordovician deformation, but neglects any shortening by localized faulting which is likely important at these crustal levels.

In contrast to the Famatinian upper crust, where shortening is characterized by open folding, cleavage development, and probable localized faulting (Turner, 1967; Astini and Dávila, 2004; Cisterna and Mon, 2014; this study), the middle crust records extensive shortening. Although deeper crustal levels are not exposed in Sierra de Narvaéz – Las Planchadas region, extensive shortening at mid-crustal levels has been recorded during the Famatinian orogeny (*ca.* 475 – 470 Ma), evidenced by development of km-scale mylonitic shear zones, variable-scale folding and subsequent generation of axial planar foliations, as well as syn-anatectic folding and shearing in migmatites in the Famatinian back-arc (Le Corre and Rosselo, 1994; Finch et al., 2017; Christiansen et al., 2019; Larrovere et al., 2020).

The apparent discrepancy between shortening magnitude at upper- and lower-crustal levels in the Famatinian arc indicates that either (a) upper-crustal shortening tends to occur in highly-localized zones which are not exposed in the studied areas, or (b) shortening in the upper crust was decoupled from that observed at mid- to lower-crustal levels. The latter option requires a detachment, a complex accommodation or transition zone, or a vertical (depth) gradient in total material addition during arc activity. A previously calculated volcanic to plutonic ratio of 1:20 for the exposed Famatinian arc (Ratschbacher et al., 2019) indicates larger volumes of igneous material emplaced with increasing depth. A greater volume with increasing depth is consistent with increased shortening at deeper crustal levels.

### *5.4. A detrital record of Famatinian arc activity*

The post-Ordovician sedimentary units record maximum depositional ages, the time span and peaks of magmatic activity of the Famatinian arc, and also inform sources of the Carboniferous and Permian strata. Prominent Famatinian-age peaks are present in all Permian and Carboniferous samples analyzed in this study. With the exception of sample BR32-2, detrital zircon age spectra are dominated by Famatinian-aged peaks (Figure 11). These age peaks tend to be clustered in two groups: Lower-Middle Ordovician (Floian – Dapingian) and early Lower Ordovician (Tremadocian). The first group is characterized by peaks at 470, 474, 469, and 472 Ma (samples BR32-2, E26, E32-2 and A78, respectively; Figure 11). The older age group is recorded in sample A24 with a main peak at 481 Ma. These two clusters support the range of Famatinian magmatic ages recorded in previous local and regional studies, generally within the range of 486 – 463 Ma (Rapela et al., 2018 and references therein). In the investigated area, the older age group coincides within uncertainty with the Tremadocian granodiorite intrusions from the Sierra de Narváez (Las Angosturas pluton) and Sierra de Las Planchadas (485 ± 7 and 485 ± 5 Ma, respectively; Rubiolo et al., 2002; Safipour et al., 2015). The younger age cluster (474 – 469 Ma) may be related to volcanic and hypabyssal igneous units of the Suri and Las Planchadas Fms., previously dated at 468 ± 3 Ma (Fanning et al., 2004). At a regional scale, both age clusters provide further evidence that the main episodes of magmatic activity of the Famatinian arc were between 468 – 472 Ma and 478 – 486 Ma (Rapela et al. 2018), and the total duration of arc volcanism recorded in Sierra de Famatina (477 – 463 Ma; Dahlquist et al., 2008; Armas et al., 2018). Furthermore, clustering of ages around *ca.* 470 Ma in samples analyzed in this study supports the postulated high magmatic addition rate during the Famatinian arc flare-up (Ratschbacher et al., 2019).

Detrital zircon age distributions indicate that Permian and Carboniferous sedimentary units of the De La Cuesta and Agua Colorada Fms. were mostly sourced from nearby Ordovician units (see above), although younger and older populations, presumably derived from other sources, are present (Figure 11). Detrital zircon samples BR32-2 and E26 both show significant peaks at *ca.* 525 Ma, 590 – 560 Ma, and 1300 – 900 Ma, age intervals widely recognized in basement rocks of the Sierras Pampeanas and southern Puna (Rapela et al., 2016). This indicates that the De La Cuesta and Agua Colorada Fms. were also sourced from Lower Cambrian and older units and/or from the Ordovician units containing inherited zircons. Zircon populations younger than Ordovician are scarce. Zircon ages and peaks in the range of 350 – 300 Ma are probably linked to Carboniferous magmatism reported in the eastern Sierras Pampeanas of Argentina and Cordillera Frontal of Argentina and Chile (Moreno et al., 2020 and references therein). Finally, the peak at 308 Ma recorded in Sample A24 provides a maximum depositional age of Middle Pennsylvanian (Moscovian) or younger for the Agua Colorada Fm. Our data confirm the late Carboniferous age assigned to the middle and upper members of this unit, previously based on the paleontological record (Vergel et al., 1993; Buatois and Mángano, 1995; Limarino et al., 2010).

### ***5.5. Further constraining the existing Famatinian upper arc geodynamic model***

Our mapping is largely consistent with previous work in the Sierra de Narváez – Las Planchadas (Cisterna et al., 2010b; Cisterna and Coira, 2014; Cisterna and Mon, 2014) but also adds further constraints to reconstructing the depositional, intrusive, and deformational environment of the Famatinian upper arc. We document a decrease in sedimentation energy (*e.g.* Figure 2 c-e, 4) away from regions of intense flow banding (centered around 27° 46.05'S, 68° 4.66'W and 27° 43.91'S, 68° 5.03'W). We interpret the two regions of intense flow banding to be volcanic necks within or immediately below volcanic edifices; volcanos shed debris off their flanks, producing a higher proportion of volcaniclastic material proximal to the necks. Shallow marine fossils with interbedded ash layers (Figure 2b, c) indicate an emergent island arc with subaerial volcanic edifices producing explosive eruptions of volcanic material. Although likely affected by later hydrothermal activity, rock geochemistry from Famatinian intrusive, volcanic, and volcaniclastic facies is consistent with an interconnected magma plumbing system, connecting plutonic and hypabyssal bodies to shallow plugs, dikes, sills, and erupted material. We clearly document syn-magmatic contractional deformation recording at least 10 – 15% shortening (Figure 6) and interpret the pervasive axial planar cleavage present within some metasediments of the Suri Fm. (yet absent in younger sedimentary rocks) to record ~E-W directed (present day orientation) Famatinian contraction contemporaneous with arc activity. The modest upper crustal shortening contrasts to more extensive shortening documented at mid-crustal levels (Le Corre and Rosselo, 1994; Finch et al., 2017; Christiansen et al., 2019; Larrovere et al., 2020). These observations are summarized in a schematic cartoon illustrating geodynamics processes and setting of the Sierra de Narváez – Las Planchadas during the Famatinian orogeny (Figure 12).

## 6. Concluding remarks

We present new mapping, geochemistry, and geochronology on rocks exposed in the Sierra de Narváez – Las Planchadas to better constrain the tectonic history and geodynamic processes acting within the upper Famatinian arc. REE trends in Famatinian arc rocks indicate the Sierra de Narváez – Las Planchadas region is a continuation of the Sierra de Famatina, lying along the main arc axis during Famatinian arc activity. Bulk rock geochemistry from Famatinian intrusive in the Sierra de Las Planchadas, volcanic, and volcaniclastic rocks support an interconnected magma plumbing system, linking plutonic and hypabyssal bodies to shallow plugs, dikes, sills, and erupted material. Although clearly affected by later deformation, we provide evidence in support of ~E-W shortening during the Ordovician. Geochemistry and structural analysis indicate that an interconnected upper-crustal (*e.g.* volcanic) and mid-crustal (*e.g.* plutonic) arc plumbing system developed during orogenic contractional deformation. New detrital geochronology on Carboniferous and Permian strata adds further constraints to the timing and duration of periods of high magmatic addition from 468 – 472 Ma and 478 – 486 Ma, during Famatinian arc activity.

## 7. Acknowledgements

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## 8. Figure Captions

**Figure 1:** Generalized outcrop map illustrating exposure of the Ordovician Famatinian orogen where it crops out in ranges of the Sierras Pampeanas, northwestern Argentina. The solid bold line denotes the boundary between the I-type and S-type granitoid belt of the Famatinian orogen and the distinction between Famatinian back-arc and magmatic arc (after Weinberg et al., 2018). The area of this study is outlined in a black box. Besides the Sierra de Narváez-Las Planchadas, exposures of the upper-crustal volcanic-sedimentary sections are limited to the Sierra de Famatina (FA) and Jagüé-Toro Negro (JTN) areas. Abbreviations for other ranges: AC: Aconquija; AM: Ambato; AN: Ancasti; CA: Capillitas; CC: Cumbres Calchaquíes; CH: Chepes; CO: Córdoba; CP: Copacabana; FI: Fiambalá; MA: Maz; PP: Pie de Palo; QU: Quilmes; SB: Sierra Brava; SL: San Luis; UL: Ulapes; UM: Umango; VE: Velasco; VF: Valle Fértil.

**Figure 2:** Field photos illustrating the sedimentology of Ordovician sedimentary rocks exposed in the Sierra de Narváez – Las Planchadas. (a) cm-scale ripples within a sandstone member of the Suri Fm. indicate shallow marine deposition. (b) Brachiopod (left), *Rusophycus* trace fossils (right), along with trilobites and gastropods (not pictured) provide further evidence for shallow marine deposition and give timing constraints on age of sedimentation (Floian to Darriwilian). (c) Typical marine facies of the Suri Fm. as described in this study with a 50 – 70 cm thick ash

bed (light colored) near the top of the outcrop. Interlayered ash deposits indicate subaerial volcanism. (d) Volcaniclastic facies of the Suri Fm. as described in this study. Volcaniclastic rocks are typically coarser grained than the marine facies but still include sedimentary structures such as cross-bedding (pictured). (e) Clastic-volcanic or volcanic-rich facies of the Suri Fm. are generally coarse to very coarse grained and include volcanic lithoclasts (rhyolitic to basaltic compositions) mixed with fine-grained marine clasts. Most clastic-volcanic rocks are massive although some preserve graded bedding and preferentially oriented clasts. We interpret these to result from high-energy submarine deposition (*e.g.* turbidity currents) originating from the slopes of proximal volcanos. (f) Lapilli within the Suri Fm. provide further evidence for subaerial volcanism coincident with sedimentation in the Ordovician.

**Figure 3:** Field photos illustrating the petrology of Ordovician igneous rocks in the Sierra de Narváez – Las Planchadas. (a) Los Angosturas granite (*i.e.* Narváez Granitoid) shows a porphyritic texture with quartz and potassium feldspar phenocrysts, consistent with relatively shallow (i.e. hypabyssal) emplacement. Mafic enclaves (lower right, upper left) are common in the Narváez Granitoid. (b) Flow banded rhyolite with lithophysae. Flow banding has been folded into a tight to isoclinal fold, consistent with high strain in the rhyolite. Note hand lens for scale. (c) Foreground: flow banded rhyolite with magmatic boudinage provides further evidence for high magmatic strain. Both (b) and (c) are outcrops we interpret as volcanic necks – discussed further in text. Background: morphology of a rhyolitic plug that intruded the Suri. Fm. This specific plug is exposed south of Río Chaschuil in the southwest map area. (d) Details of flow banding and lithophysae in rhyolite embossed by wind erosion. (e) Basalt dike (1 - 1.5 m thick) cutting across marine facies rocks of the Suri Fm. (f) Rhyolite body parallel to bedding in the

Suri Fm. (grey-colored bedding can be seen below the pinkish rhyolite) indicates subaerial deposition by flow or very shallow sill intrusion.

**Figure 4:** 1:100,000 geologic map of the Sierra de Narváez-Las Planchadas overlain on greyscale satellite imagery. Note approximate line of section (Figure 5), and locations of geochronology and geochemistry samples.

**Figure 5:** Cross-section along approximate line of section A-A' (Figure 4) through the northern Sierra de Narváez-Las Planchadas area.

**Figure 6**: Field photos illustrating the structures present within the Sierra de Narváez – Las Planchadas. (a) The Vuelta de Las Tolas anticline exposed south of the Río Chaschuil, folding sediments of the Suri Fm. and volcanics of the Las Planchadas Fm. Look direction is SSW. Basalts and shales in the core of the anticline preserve a steeply-dipping axial planar cleavage; based on the presence of an axial planar cleavage, we interpret this fold to record chiefly Famatinian (Ordovician) shortening. (b) Magmatic mullions developed within the Las Planchadas rhyolite indicate syn-magmatic shortening in the Ordovician. Mullion axes are subparallel to regional fold axes (look direction of the photograph is ~N) and truncate cleavage within shales of the Suri Fm. (red dashed line). (c) Magmatic mullion developed in the Las Planchadas Fm. dacite intruding Suri Fm. as in (b). Look direction is ~NNE.

**Figure 7:** Contoured lower hemisphere, equal-area projections of structural measurements, plotted in Stereonet 9 (www.geo.cornell.edu/geology/faculty/RWA/programs/stereonet). All best-

fit orientations are recorded using the right-hand rule convention. (a) Poles to bedding in Ordovician metasedimentary rocks of the Suri and Las Planchadas Fms. Best-fit axial plane to folding in Ordovician bedding: 193/75. (b) Poles to bedding of sedimentary rocks younger than Ordovician, including the Agua Colorada, De La Cuesta, Tambería, and Guanchín Fms. Best-fit axial plane to folding in bedding younger than Ordovician: 014/88. (c) poles to the axial planar cleavage developed within Ordovician metasedimentary rocks. Best-fit cleavage plane: 026/84. Note the difference between best-fit axial plane in (a) and best-fit axial planar cleavage in (c), which is discussed further in the main text.

**Figure 8:** Solution cleavage within the Suri Fm. (a) An example of the steeply-dipping spaced cleavage developed within a brachiopod-rich shale. The cleavage forms an anastomosing network around fossilized brachiopods. The pencil for scale is oriented ~N-S. (b) At the micro-scale, the cleavage is clearly the result of dissolution of soluble phases. In this instance, calcite grains are truncated by spaced solution seams. Plane polarized light.

**Figure 9:** Petrographic images of a selection of rock units from the Sierra de Narváez – Las Planchadas. (a) Flow banded rhyolite (sample B17) with lithophysae that are entirely recrystallized to chalcedony. Some cavities are filled with calcite. The top half is in plane polarized light that allows better visualization of the flow banding, while the bottom half is in cross polarized light showing the recrystallized texture. (b) Phenocrysts of sanidine, plagioclase and quartz in sample B58. Sanidine and to a lesser extent, plagioclase, show evidence of resorption in form of embayments. (c) Glomerocryst of sanidine, plagioclase, and quartz in sample B58. d) Devitrified, poorly welded tuff with lithic clasts ranging from basalt to rhyolite,

devitrified glass shards, and phenocrysts in sample E56. (e) Biotite altered into Fe-rich chlorite, embedded in a chalcedony groundmass (sample C16). Plagioclase phenocrysts surrounding chloritized biotite are strongly sericitized. (f) Granophyric granite texture records parallel fractures healed with quartz, indicating cataclastic deformation (sample A60). Sample numbers are indicated in the upper-right corner of each photomicrograph and sample locations are marked on the map (Figure 4).

**Figure 11:** U-Pb detrital zircon ages presented in this study. Individual ages (open circles) plotted along X-axis with binned histograms (open boxes) and age spectra (blue fill). Individual peaks labeled with ages. Full age spectra on the left; corresponding detailed (reduced time span) spectra on the right. Age locations are indicated on the map (Figure 4).

**Figure 12:** (a) Total alkali vs. silica variation diagram illustrating the classification of plutonic rocks after Cox et al. (1979) for the granitic samples of the Sierra de Narváez. The alkaline/mid-alkaline/subalkaline magmatic lineages are defined by sigma isopleths (after Rittmann, 1957). (b) $K_2O$ vs. $SiO_2$ diagram with classification boundaries after Le Maitre et al. (1989) for the igneous rocks of the studied area. (c) Chondrite-normalized (after Nakamura, 1974) REE plots of igneous rocks of the study area. The grey area is given by one rhyolite and two samples of the Ñuñorco granite of the central part of Sierra de Famatina (data are taken from Pankhurst et al., 2000 and Dahlquist et al., 2008). (d) Total alkali vs. silica diagram (after Le Maitre et al., 1989) for the volcanic rocks of the studied area. The diagram also shows sigma isopleths. (e) log $Zr/TiO_2$ vs. $SiO_2$ diagram (after Winchester & Floyd 1977) for classification of volcanic rocks using incompatible element ratios. (f) Th/Yb vs. Ta/Yb plot (after Pearce, 1983) for the basalts of

the studied area. The gabbro and basalt fields are taken from Coira et al. (2009) and Alasino et al. (2016). E56 ($SiO_2$>81%) is not plotted in (b) and (d). Sample locations are marked on the map (Figure 4).

**Figure 13:** Schematic cartoon of the upper-most Famatinian arc summarizing the contemporaneous intrusive, sedimentation, and deformational processes recorded in the Sierra de Narváez – Las Planchadas region. Active volcanism and construction of subaerial volcanic edifices in an otherwise marine environment characterized by high energy volcanic-rich sedimentation proximal to the volcanic centers, transitioning to low energy, shallow marine deposition punctuated by large mass wasting deposits in more distal regions. Synchronous with igneous activity and sedimentation, E-W oriented contraction forms upright open folds with a penetrative axial planar cleavage and magmatic mullions in hypabyssal bodies.

## 9. Table captions

**Table 1:** X-ray fluorescence major oxide and trace element concentrations from Ordovician igneous and sedimentary rocks from the Sierra de Narváez – Las Planchadas. Sample locations are plotted on Figure 4.

## 10. Supplementary Material

**Table S1:** U-Pb LA-ICP-MS standard analyses. Unknown analyses are listed in table S2. See main text for further discussion.

**Table S2:** U-Pb LA-ICP-MS detrital geochronology data table. Analyses in bold font are those included in the final spectra (Figure 11). Sample locations are plotted on the map (Figure 4).

**Table S3:** U-Pb LA-ICP-MS systematic uncertainties for samples presented in this study.

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Table 1. Major and trace element concentrations of igneous rocks from the Sierra de Narváez - Las Planchadas

| | Las Angosturas pluton | | Volcanic mafic rocks | | | | Volcanic felsic rocks | | | | | | Volcaniclastic rocks | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample number | C76 | BR37-2 | C31B | A58 | A27-2 | D24-1 | E56 | C42 | BR36 | B58 | B17 | B4 | E37A | C50 |
| wt% | | | | | | | | | | | | | | |
| $SiO_2$ | 68.45 | 72.99 | 54.01 | 50.39 | 51.12 | 50.92 | 81.59 | 76.78 | 68.54 | 76.3 | 78.9 | 73.48 | 57.22 | 48.44 |
| $TiO_2$ | 0.42 | 0.33 | 1.22 | 0.95 | 0.75 | 0.71 | 0.15 | 0.15 | 0.51 | 0.19 | 0.08 | 0.16 | 0.67 | 0.82 |
| $Al_2O_3$ | 14.68 | 13.59 | 15.98 | 17.85 | 15.29 | 14.46 | 8.72 | 12.69 | 15.4 | 12.15 | 11.85 | 12.37 | 15.35 | 16.64 |
| $FeO^t$ | 3.75 | 3.07 | 8.94 | 7.87 | 8.26 | 8.09 | 1.23 | 1.61 | 3.58 | 1.66 | 0.77 | 2.56 | 6.56 | 9.39 |
| MnO | 0.09 | 0.06 | 0.2 | 0.28 | 0.16 | 0.17 | 0.06 | 0.04 | 0.08 | 0.02 | 0.01 | 0.05 | 0.13 | 0.19 |
| MgO | 1.48 | 1.17 | 6.07 | 7.99 | 4.85 | 3.85 | 1.55 | 0.23 | 1.66 | 0.57 | 0.09 | 0.51 | 2.03 | 6.84 |
| CaO | 1.59 | 0.69 | 6.95 | 9.77 | 5.72 | 10.15 | 0.1 | 0.58 | 1.99 | 0.68 | 0.65 | 0.64 | 8.91 | 9.56 |
| $Na_2O$ | 3.3 | 6.03 | 5.08 | 1.98 | 5.07 | 3.61 | 0 | 4.84 | 5.3 | 2.3 | 3.15 | 4.52 | 7.79 | 2.51 |
| $K_2O$ | 3.85 | 0.38 | 0.25 | 1.58 | 0.48 | 0.74 | 6.23 | 2.7 | 0.76 | 5.74 | 4.24 | 3.09 | 0.39 | 1.64 |
| $P_2O_5$ | 0.12 | 0.09 | 0.15 | 0.21 | 0.11 | 0.13 | 0.04 | 0.02 | 0.11 | 0.04 | 0.01 | 0.02 | 0.11 | 0.15 |
| LOI | 1.58 | 1.12 | -- | -- | 7.25 | 6.77 | -- | -- | 1.68 | -- | -- | 0.9 | -- | 3.22 |
| Total | | | | | | | | | | | | | | |
| *ppm* | | | | | | | | | | | | | | |
| Cs | 1.4 | 0.2 | -- | -- | 0.4 | 0.8 | -- | -- | 0.6 | -- | -- | 0.4 | -- | 0.6 |
| Rb | 109 | 13 | 4.19 | 72.4 | 18 | 22 | 153 | 65.8 | 26 | 146 | 156 | 79 | 75.2 | 61 |
| Sr | 124 | 81 | 130 | 190 | 156 | 335 | 13.4 | 89.1 | 244 | 92.1 | 51.5 | 109 | 83.8 | 206 |
| Ba | 630 | 69 | 137 | 246 | 144 | 216 | 852 | 426 | 198 | 490 | 507 | 636 | 116 | 292 |
| La | 38.8 | 35.6 | -- | -- | 11 | 10.4 | -- | -- | 37.4 | -- | -- | 22.6 | -- | 10.1 |
| Ce | 81.5 | 76 | -- | -- | 24.4 | 23.4 | -- | -- | 79 | -- | -- | 52.2 | -- | 23.6 |
| Pr | 9.17 | 8.72 | -- | -- | 3 | 2.93 | -- | -- | 8.87 | -- | -- | 6.19 | -- | 3.05 |
| Nd | 34.5 | 31.9 | -- | -- | 13.4 | 12.5 | -- | -- | 34.1 | -- | -- | 23.8 | -- | 14.1 |
| Sm | 7.52 | 7.3 | -- | -- | 3.29 | 2.93 | -- | -- | 6.89 | -- | -- | 6.2 | -- | 3.32 |
| Eu | 1.18 | 1.08 | -- | -- | 0.88 | 0.94 | -- | -- | 1.22 | -- | -- | 1.01 | -- | 1.11 |
| Gd | 6.63 | 6.58 | -- | -- | 3.44 | 3.01 | -- | -- | 5.7 | -- | -- | 6.84 | -- | 3.48 |
| Tb | 1.07 | 1.21 | -- | -- | 0.56 | 0.51 | -- | -- | 0.88 | -- | -- | 1.23 | -- | 0.54 |
| Dy | 6.46 | 7.49 | -- | -- | 3.51 | 3.18 | -- | -- | 5.2 | -- | -- | 8.19 | -- | 3.41 |
| Ho | 1.28 | 1.54 | -- | -- | 0.72 | 0.66 | -- | -- | 0.96 | -- | -- | 1.71 | -- | 0.69 |
| Er | 3.78 | 4.4 | -- | -- | 2.08 | 1.98 | -- | -- | 2.78 | -- | -- | 5.17 | -- | 1.99 |
| Tm | 0.53 | 0.65 | -- | -- | 0.31 | 0.28 | -- | -- | 0.39 | -- | -- | 0.79 | -- | 0.28 |
| Yb | 3.68 | 4.07 | -- | -- | 2.12 | 1.77 | -- | -- | 2.56 | -- | -- | 5.47 | -- | 2.03 |
| Lu | 0.51 | 0.60 | -- | -- | 0.31 | 0.26 | -- | -- | 0.38 | -- | -- | 0.84 | -- | 0.30 |
| U | 1.95 | 2.15 | -- | -- | 0.7 | 0.73 | -- | -- | 1.94 | -- | -- | 3.32 | -- | 0.5 |
| Th | 14.5 | 13.7 | 2.09 | 3.15 | 3.31 | 2.62 | 4.12 | 12.2 | 13.6 | 13.4 | 20.6 | 15.1 | -- | 2.01 |
| Y | 37 | 43.8 | 25.1 | 19.9 | 20 | 18.9 | 24.7 | 57.7 | 28.1 | 33.1 | 38.1 | 49.5 | 11.8 | 19.1 |
| Nb | 10.9 | 10.7 | 7.34 | 6.3 | 3 | 2.7 | 15.4 | 15.2 | 10.6 | 24.8 | 20.6 | 7.4 | 5.37 | 2.6 |
| Zr | 148 | 125 | 93.4 | 76.6 | 76 | 59 | 113 | 207 | 144 | 138 | 113 | 175 | 44.1 | 63 |
| Hf | 4.8 | 4.2 | 5.24 | 4.2 | 2.5 | 1.8 | 2.06 | 6.07 | 4.4 | 3.1 | 5.15 | 5.7 | -- | 1.9 |
| Ta | 1.19 | 1.09 | -- | -- | 0.42 | 0.38 | -- | -- | 1.16 | -- | -- | 0.97 | -- | 0.37 |
| Sc | 13 | 11 | 42 | 37.8 | 34 | 32 | 5.15 | 6.07 | 14 | 6.2 | 3.09 | 8 | 32.2 | 37 |
| Ga | 17 | 13 | 18.8 | 16.8 | 16 | 15 | 8.2 | 18.2 | 18 | 12.4 | 14.4 | 18 | 8.6 | 16 |
| Cr | 50 | 50 | 40 | 272 | 100 | 140 | 4 | 6 | 90 | 3 | -- | 30 | 118 | 190 |
| Co | 10 | 9 | -- | -- | 31 | 29 | -- | -- | 12 | -- | -- | 3 | -- | 39 |
| Ni | < 20 | < 20 | 23.1 | 81.9 | 20 | 30 | -- | -- | 20 | -- | -- | < 20 | 16.1 | 50 |
| V | 59 | 44 | 299 | 266 | 223 | 181 | 18 | 6.1 | 75 | 21 | 8.2 | 11 | 166 | 250 |
| Pb | 19 | 6 | 12.6 | 21 | 10 | 9 | 4.12 | 8.1 | 17 | 21.7 | -- | 9 | -- | 30 |

*Note:* Total iron measured as $Fe_2O_3$ but expressed as $FeO^{total}$. Double hyphen: *not determined*.

Highlights:

- The Sierra de Narváez - Las Planchadas preserve remnants of the Famatinian arc along the main arc axis
- In this region periods of high magma addition occurred from 468-472 and 478-486 million years ago
- Arc plumbing developed and was active during contractional deformation
- Upper crustal shortening here is significantly less than what is documented at mid-crustal levels

## Author statement

All authors were involved in the following: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, review & editing.

**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: