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Tectonothermal evolution and exhumation history of the Paleozoic Proto-Andean Gondwana margin crust: The Famatinian Belt in NW Argentina

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ABSTRACT

We studied the P–T–t evolution of a mid-crustal igneous-metamorphic segment of the Famatinian Belt in the eastern sector of the Sierra de Velasco during its exhumation to the upper crust. Thermobarometric and geochronological methods combined with field observations permit us to distinguish three tectonic levels. The deepest Level I is represented by metasedimentary xenoliths and characterized by prograde isobaric heating at 20–25 km depth. Early/Middle Ordovician granites that contain xenoliths of Level I intruded in the shallower Level II. The latter is characterized by migmatization coeval with granitic intrusions and a retrograde isobaric cooling P–T path at 14–18 km depth. Level II was exhumed to the shallowest supracrustal Level III, where it was intruded by cordierite-bearing granites during the Middle/Late Ordovician and its host-rock was locally affected by high temperature–low pressure HT/LP metamorphism at 8–10 km depth. Level III was eventually intruded by Early Carboniferous granites after long-term slow exhumation to 6–7 km depth. Early/Middle Ordovician exhumation of Level II to Level III (Exhumation Period I, 0.25–0.78 mm/yr) was faster than exhumation of Level III from the Middle/Late Ordovician to the Lower Carboniferous (Exhumation Period II, 0.01–0.09 mm/yr). Slow exhumation rates and the lack of regional evidence of tectonic exhumation suggest that erosion was the main exhumation mechanism of the Famatinian Belt. Widespread slow exhumation associated with crustal thickening under a HT regime suggests that the Famatinian Belt represents the middle crust of an ancient Altiplano–Puna-like orogen. This thermally weakened over-thickened Famatinian crust was slowly exhumed mainly by erosion during ~180 Myr.

1. Introduction

Unravelling the exhumation history of rocks in different geodynamic settings has become a major focus of recent research in petrology since exhumation processes reflect the evolution of the orogen and have great influence on the formation of orogenic topography (Ring et al., 1999). Fossil orogens are exhumed relics of crustal segments which frequently contain a comprehensive record of petrogenetic processes such as deformation, metamorphism, magmatism, and partial melting as well as the pressure–temperature–time (P–T–t) paths that rocks underwent during the orogenic period (e.g. Brown, 2010; Maruyama et al., 2010). The study of the P–T evolution and exhumation history of a fossil orogen provides direct insights into geodynamic processes and exhumation mechanisms of crustal rocks. The Famatinian Belt represents the middle- to upper crust of a fossil Andean-type orogen, which developed along the proto-Pacific margin of Gondwana in Paleozoic times. Several interpretations about the origin and evolution of the magmatism (e.g. Rapela et al., 1992; Toselli et al., 1996; Saavedra et al., 1998; Pankhurst et al., 1998, 2000; Rossi et al., 2002), and the metamorphic evolution of the Famatinian Belt (e.g. Vujovich, 1994; Dahlquist and Baldo, 1996; Hauzenberger et al., 2001; Lucassen and Becchio, 2003; Büttner et al., 2005; Otamendi et al., 2008; Larrovere et al., 2011) were proposed from petrologic studies in different outcropping crustal segments along this orogen. The tectonic scenario in which the Famatinian crust evolved has been envisaged in two contrasting models: (1) significant back-arc extensional shearing and crustal thinning (e.g. Büttner et al., 2005; Büttner, 2009) and (2) strong compression and crustal thickening (e.g. Willner et al., 1987; Whitmeyer and Simpson, 2004) although both models invoke high heat input by magmatic advection from the upper mantle to explain high T/P conditions. Ordovician high T back-arc extension has been interpreted from P–T–d (deformation)–t paths and shear-indicator kinematic analysis in the migmatitic basement assuming tilting of the present-day shear zone orientations during the Andean orogeny (Büttner et al., 2005; Büttner, 2009), coeval deposition of thick marine sediments over this basement (Büttner, 2009) and generation of

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ferrosilicic (high iron and silica) magmas which would have ascended from a deep cold diapir or mantle wedge plume (Fernández et al., 2008). Ordovician high T compression has been proposed on the basis of kinematic analysis using the present-day orientation of shear zones and associated evidence of strong shortening (e.g. tight folding) throughout the migmatite basement (Willner et al., 1987; Whitmeyer and Simpson, 2004; Wegmann et al., 2008). The exhumation history (rates and mechanisms) of different segments of the Famatinian Belt, which would yield additional information about geodynamic processes and extensional/compressional tectonic regimes along this orogen, was not yet addressed.

The Sierra de Velasco is located in the zone between the main arc and the back arc of the Famatinian Belt. It constitutes a key area to study exhumation rates since outcrops representing magmatic and metamorphic events from different crustal levels which occurred in different geologic time are exposed. This paper is aimed at providing information on the timing of mid- and supracrustal magmatic and metamorphic events in the eastern sector of the Sierra de Velasco. We combined new and previously published results from monazite and zircon dating, thermobarometry and field data to calculate exhumation rates and infer possible exhumation mechanisms.

2. Geologic setting

2.1. The Famatinian Belt

The Famatinian Belt is a Paleozoic subduction-related continental magmatic arc and its metasedimentary host-rocks formed during the Famatinian Orogenic Cycle along the proto-Andean margin of Gondwana (Aceñolaza and Toselli, 1973). The middle to upper crust of this orogen crops out along a N–S trending belt of at least 800 km length and 400 km width and form the Paleozoic basement of the Sierras Pampeanas in central and NW-Argentina (Fig. 1a). The Famatinian metasedimentary basement is broadly composed of psammopelitic high temperature medium/low pressure migmatite and subordinated lower grade phyllite and schist. Evidence of strong folding and ductile west-directed reverse shearing parallel to the migmatitic layering is widely observed (e.g. Willner et al., 1987; Büttner et al., 2005; Larrovere et al., 2008; Büttner, 2009). This high-T compressive deformation took place during an episode of crustal thickening which occurred probably in Cambrian and Early Ordovician times (Willner et al., 1987). Similar peak metamorphic conditions in migmatite (650–800 °C and 4–7 kbar) were calculated in different regions of the Famatinian Belt such as the Sierras de Quilmes (Büttner et al., 2005), Ancasti–Ambato–Aconquija (Larrovere et al., 2011), Valle Fértil–La Huerta (Otamendi et al., 2008) and San Luis (Delpino et al., 2007), suggesting that similar deepest paleo-depths of the Famatinian crust are exposed over a wide area. U–Pb and Sm–Nd ages of the high-T metamorphism throughout the orogen are ~530–500 Ma and ~470–440 Ma and overlap spatially (Pankhurst et al., 1998; Lucassen et al., 2000; Lucassen and Becchio, 2003; Büttner et al., 2005), indicating long-lived both high-T conditions within the Famatinian crust and subduction along western Gondwana. The Famatinian magmatic arc comprises two main NNW–SSE trending belts dominated by calc-alkaline granitic rocks (Pankhurst et al., 2000), a metaluminous I-type belt in the west, and a peraluminous S-type belt in the east (Fig. 1a). Intrusion of both granitic belts occurred from the Early to the Middle/Late Ordovician (~490–450 Ma; e.g. Rapela et al., 1992; Saavedra et al., 1998; Pankhurst et al., 1998, 2000; Büttner et al., 2005; Steenken et al., 2006), indicating that orogen-scale high-T metamorphism and plutonic activity were broadly coeval (e.g. Pankhurst et al., 2000; Rossi et al., 2002).

Ordovician Famatinian rocks were cut by numerous NNW–SSE trending east-dipping shear belts characterized by reverse west-directed thrusting (e.g. López and Toselli, 1993; Le Corre and Rossello, 1994). Geochronological evidence from syn-kinematic minerals suggests that these belts were active in Silurian and Devonian times. In the westernmost part of the Famatinian Belt, $^{40}Ar/^{39}Ar$ ages of medium-grade shear zones are around 430 Ma (Castro de Machuca et al., 2008). Medium- to low-grade brittle–ductile shear zones central part of the Famatinian Belt were still active in the Early Devonian (Sm/Nd isochron in garnet of ~400 Ma; Höckenreiner et al., 2003). It suggests that compressive tectonics was long-lived and accompanied the exhumation of the Famatinian crust. After a long period (~100 Myr) of reduced magmatism, widespread intrusion of post-tectonic supra-crustal granitic plutons occurred in the Devonian/Carboniferous (340–360 Ma; Grosse et al., 2009 and references therein). The minimum age of final exhumation of the Famatinian crust is indicated by Devonian/Carboniferous sediments overlying Ordovician metamorphic and granitic rocks as well as Carboniferous plutons at various locations (Lucassen et al., 2000; Pieroni and Georgieff, 2007).

Although it is broadly accepted that the Famatinian Belt is a subduction-related orogen (e.g. Toselli et al., 1996; Pankhurst et al., 1998), a Central Andean-type scenario was recently proposed by Lucassen and Franz (2005). They found striking similarities between the Cenozoic Altiplano–Puna plateau and the Famatinian Belt such as: (a) the widely distributed Ordovician migmatite basement of the Famatinian Belt exposing maximal paleo-depths of ~25 km may be a fossil analogue of the wide zone of partially melted rocks at ~15–25 km depth represented by the present-day seismic Altiplano Low-Velocity Zone (ALVZ; e.g. Heit et al., 2008); (b) widespread felsic calc-alkaline arc magmatism without significant mantle contribution in both orogens; and (c) lack of tectonically exhumed deep crustal high-pressure rocks (e.g. eclogites and blueschists). This Cenozoic–Paleozoic tectonic analogy is further discussed in Section 8.3.

Based on the across-arc tectonic subdivision of Otamendi et al. (2008) of the Famatinian Belt, we distinguish the fore-arc zone characterized by an accretionary wedge along the western side of the Sierra de Valle Fértil (Vujovich, 1994) and Famatina, the main arc zone including major batholiths such as the Sierras de Velasco and Chepes and the back-arc zone located east from the main arc and including the Sierras de Aconquija, Ambato, Ancasti and San Luis. Within this context the study area is located in the easternmost side of the main Famatinian arc.

2.2. The Sierra de Velasco

The Sierra de Velasco constitutes one of the most complete records of magmatic activity in the middle to upper crust during the Famatinian Orogeny. It is mainly composed of metaluminous and peraluminous Ordovician granitoids intruded by Carboniferous post-tectonic plutons (Fig. 1b). The pre-magmatic metasedimentary host-rock is present as small outcrops along the eastern flank of the Sierra and is classically referred as the southern equivalent of the La Cébila Formation (LCF) of the Sierra de Ambato (e.g. González Bonorino, 1951; Verdecchia and Baldo, 2010). The I-/S-type limit is represented in the central-southern sector of the Sierra de Velasco (Bellos, 2005). Thermobarometric studies in Ordovician plutons of the western flank of the Sierra de Velasco indicate emplacement in the middle crust (~5–6 kbar; Rossi et al., 2005; Rossi and Toselli, 2005). Cordierite-bearing granitoids are observed as small bodies spatially associated with the S-type belt (Fig. 1b), although they also intruded metaluminous I-type granodiorites in the Sierra de Chepes at upper-crustal levels in Ordovician times (Dahlquist et al., 2005). U–Pb ages obtained in the Sierra de Velasco and adjacent sectors indicate that the I- and S-type magmatism occurred in the Early to Middle Ordovician (~480–460 Ma; e.g. Pankhurst et al., 2000; Rapela et al., 2001; Dahlquist et al., 2008). The Ordovician granitoids were deformed by inverse shear represented by NNW–SSE trending belts crosscutting the Sierra (Rossi et al., 1999; Bellos, 2005). Lithological continuity on both sides of the shear zones suggests that relative movement of the blocks was relatively small and did not juxtapose different crustal segments. Early Carboniferous post-tectonic granites intruded the Ordovician