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Metamorphic and geochronogical study of the Triassic El Oro metamorphic complex, Ecuador: Implications for high-temperature metamorphism in a forearc zone

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ABSTRACT

In the forearc of the Andean active margin in southwest Ecuador, the El Oro metamorphic complex exhibits a well exposed tilted forearc section partially migmatized. We used Raman spectroscopy on carbonaceous matter (RSCM) thermometry and pseudosections coupled with mineralogical and textural studies to constrain the pressure–temperature (*P–T*) evolution of the El Oro metamorphic complex during Triassic times. Our results show that anatexis of the continental crust occurred by white-mica and biotite dehydration melting along a 10 km thick crustal domain (from 4.5 to 8 kbar) with increasing temperature from 650 to 700 °C. In the biotite dehydration melting zone, temperature was buffered at 750–820 °C in a 5 km thick layer. The estimated average thermal gradient during peak metamorphism is of 30 °C/km within the migmatitic domain can be partitioned into two apparent gradients parts. The upper part from surface to 7 km depth records a 40–45 °C/km gradient. The lower part records a quasi-adiabatic geotherm with a 10 °C/km gradient consistent with an isothermal melting zone. Migmatites U–Th–Pb geochronology yielded zircon and monazite ages of 229.3 ± 2.1 Ma and 224.5 ± 2.3 Ma, respectively. This thermal event generated S-type magmatism (the Marcabeli granitoid) and was immediately followed by underplating of the high-pressure low-temperature (*HP-LT*) Arenillas–Panupalí unit at 225.8 ± 1.8 Ma. The association of high-temperature low-pressure (HT-LP) migmatites with HP-LT unit constitutes a new example of a paired metamorphic belt along the South American margin. We propose that in addition to crustal thinning, underplating of the Piedras gabbroic unit before 230 Ma provided the heat source necessary to foster crustal anatexis. Furthermore, its MORB signature shows that the asthenosphere was involved as the source of the heat anomaly. S-type felsic magmatism is widespread during this time and suggests that a large-scale thermal anomaly affected a large part of the South American margin during the late Triassic. We propose that crustal anatexis is related to an anomaly that arose during subduction of the Panthalassa ocean under the South American margin. Slab verticalization or slab break-off can be invoked as the origin of the upwelling of the asthenosphere.

1. Introduction

While the generation of *HP-LT* rocks, especially blueschist facies assemblage, is characteristic of a subduction setting (e.g., Ernst, 1988; Guillot et al., 2009), *HT-LP* rocks can be produced in a wide range of geological settings. In modern belts, *HT-LP* rocks and associated crustal anatexis (S-type magmatism) are typically generated in collisional orogens (Hodges, 2000). In such a setting, HT conditions are reached either by crustal thickening or by post-orogenic collapse (Gardien et al., 1997). Crustal magma generation occurs on a timescale of 10 to 30 Ma and can produce large volumes of granites (Thompson and Connolly, 1995). In a subduction context, granitoids are usually of I-type and are not associated with HT-LP metamorphism, especially in a forearc setting (Brown, 2007; Huppert and Sparks, 1988).

In the present forearc region of the Andean margin of southwest Ecuador, the El Oro metamorphic complex (Fig. 1) exhibits a continental sequence composed of metasediments (El Tigre and La Victoria units), partially molten metasediments (La Bocana unit) and intruded

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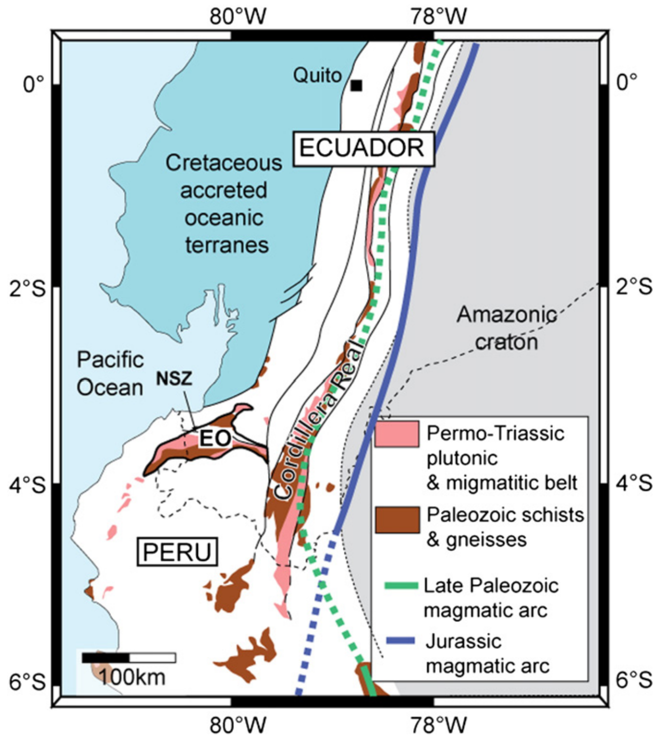

Fig. 1. Simplified geological map of Ecuador and northern Peru modified after Chew et al. (2007) showing the location of the El Oro metamorphic complex. EO, El Oro; NSZ, Naranjo Shear Zone. Continuous line: documented magmatic arc position, dashed line: inferred magmatic arc position.

by S-type granitoids (Marcabeli and El Prado plutonic rocks), juxtaposed with amphibolitic metagabbros (Piedras unit) and blueschist facies metabasalts (Arenillas–Panupalí unit) (Fig. 2). Because of the subvertical structures, this complex has been interpreted either as a shear zone active during the Triassic (Aspden et al., 1995), or as a remnant of a forearc zone tilted during a major tectonic event in the Late Triassic (Gabriele, 2002). However, little is known about the geological structures of the continental sequence and its relationships with the Piedras metagabbroic unit and the Arenillas–Panupalí blueschist unit.

Here, we focus our study on the *HT-LP* Triassic rocks of the El Oro metamorphic complex (Fig. 2). Our aims are to: (1) characterize the deformation of those units; (2) estimate the peak metamorphic *P–T* conditions; (3) age of migmatization; and (4) propose a model for the *HT-LP* gradient and the crustal anatexis associated with underplating of *HP-LT* rocks. Here we present the results obtained by combining field work, textural observations, mineralogical identification, geothermobarometry and geochronological studies. The analytical methods are presented in the Appendix A.

2. Geological setting and previous studies

In SE Ecuador various metamorphic terranes of both continental and oceanic affinity form the El Oro metamorphic complex (Aspden et al., 1995; Feininger, 1978). This complex is bounded to the south by the Cretaceous volcano-sedimentary sequence of the Celica–Lancones basin (Jaillard et al., 1996, 1999), to the NE by Tertiary volcanic deposits and to the NW by Cenozoic, recent sedimentary deposits (Fig. 2). This complex is characterized by its forearc position and by discordant E–W striking structures, within the NNE striking Andean orogenic belt (Fig. 1). The Late Paleozoic subduction related magmatic arc is known to occur within the Cordillera Central of Colombia (Vinasco et al., 2006), in NW Peru (Mišković, et al., 2009), and a Jurassic magmatic arc is known in Colombia and Ecuador, lying in the Subandean Zone (Jaillard et al., 2000). Consequently, since at least Carboniferous times, the El Oro metamorphic complex has been located in a forearc position relative to Pacific subduction zone (Fig. 1).

Three tectono-metamorphic groups are distinguished for the El Oro metamorphic complex:

(1) The Biron Complex, North of the La Palma–Guayabo Shear Zone (Fig. 2), consists of metasediments, migmatitic paragneisses, granitoids, metadiorites and amphibolites with a N-MORB-type geochemical affinity (Gabriele, 2002). Ar–Ar radiometric datings on biotite in migmatites and in metadiorites yielded cooling ages of 75.5 ± 2.3 Ma and 78.4 ± 0.5 Ma, respectively. Pb–Pb dating on monazites yielded ages of 78 ± 1 Ma and 82 ± 1 Ma, and three U–Pb zircon analyses plot on a reverse discordia with a lower intercept at 200 ± 30 Ma (Noble et al., 1997). Noble et al. (1997) interpreted the lower intercept at 200 ± 30 Ma as the age of crystallization of the granitoid, and attributed the younger monazite ages to a later episode of deformation and metamorphism.

(2) South of the La Palma–Guayabo shear zone (Fig. 2), the Raspas complex (Feininger, 1980) consists of an ophiolitic massif, the El Toro metaperidotitic unit, and the Raspas eclogitic unit (Gabriele et al., 2003; John et al., 2010). The Lu–Hf ages of John et al. (2010) from the Raspas complex indicate that the ophiolite underwent prograde HP metamorphism at around 130 Ma. Radiometric dating yielded an age of 127–123 Ma (Ar/Ar on phengite), which was interpreted as the age of underplating of the Raspas eclogitic complex beneath the Ecuadorian margin (Feininger and Silberman, 1982; Gabriele, 2002; John et al., 2010).

(3) The El Oro paired metamorphic belt is located between the Raspas complex and the Cretaceous Celica–Lancones Basin (Figs 1 & 2) and consists of late Paleozoic sediments (Martínez, 1970) metamorphosed during the Triassic (Aspden et al., 1995), juxtaposed with the Piedras gabbroic unit (Aspden et al., 1992b) and with the Arenillas–Panupalí blueschist unit metamorphosed in the Triassic (Gabriele, 2002). From south to north (Fig. 2), the continental sequence is composed of the El Tigre and La Victoria low-to-high-grade metapelitic units, intruded by the Marcabeli S-type granitoid at 227 ± 0.5 Ma (U–Pb on zircon, Noble et al., 1997) and of the La Bocana migmatitic unit dated at 219 ± 22 Ma (Sm/Nd whole-rock/garnet isochron; Aspden et al., 1995). In the Piedras metagabbroic unit, U–Pb ages on zircon are 221 ± 17 Ma (Noble et al., 1997) and Ar–Ar ages on amphibole yielded an age of 226 ± 1.8 Ma (Gabriele, 2002). Geochemical studies indicate a MORB-type affinity for the Piedras gabbroic unit (Aspden et al., 1995; Bosch et al., 2002; Gabriele, 2002). Both the Piedras and the Arenillas–Panupalí units were retrogressed under greenschist-facies conditions (Gabriele, 2002).

The El Tigre unit dips approximately to the north (50–60°), and is composed of turbidites (Aspden et al., 1992a). On its southern boundary the El Tigre unit is unconformably overlain by the Cretaceous sediments of the Celica–Lancones basin. In the north, the appearance of chlorite and biotite (Fig. 2) marks a gradational transition zone between the low metamorphic grade El Tigre unit and the moderate- to high-grade La Victoria unit. The La Victoria unit comprises a sequence of metapelites and metapsammites similar to that of the El Tigre unit. To the north, the La Victoria unit is typically composed of biotite ± muscovite ± fibrolite, albite and quartz with andalusite porphyroblasts. The Marcabeli S-type granitoid into the La Victoria unit is an elongated E–W trending laccolithic body. This pluton principally consists of medium-grained biotite ± muscovite granodiorites, with hornblende-rich xenoliths (Aspden et al., 1995). The contact between the La Victoria unit and the La Bocana unit has been interpreted as a syn- to late-magmatic dextral shear zone (Aspden et al., 1995), which is coeval with sillimanite crystallization (Feininger, 1978). These shear zones show a sub-vertical foliation. North of Marcabeli, Feininger (1978) mapped a folded contact between the La Victoria and the La Bocana unit (Fig. 2), with a lens of the La