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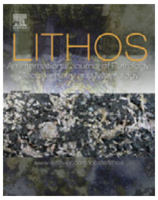

Distinguishing between in-situ and accretionary growth of continents along active margins

Ryan Cochrane [a,*], Richard Spikings [a], Axel Gerdes [b,c], Wilfried Winkler [d], Alexey Ulianov [e], Andres Mora [f], Massimo Chiaradia [a]

[a] Department of Mineralogy, University of Geneva, Switzerland
[b] Institute of Geosciences, Mineralogy, J. W. Goethe University, Frankfurt 60438, Germany
[c] Department of Earth Sciences, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa
[d] Geological Institute, ETH Zürich, Switzerland
[e] Institute of Mineralogy and Geochemistry, University of Lausanne, Switzerland
[f] Instituto Colombiano del Petróleo-Ecopetrol, Bucaramanga, Colombia

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ABSTRACT

Active continental margins represent both sites of crustal loss by tectonic erosion, and gain by juvenile magmatism and oceanic arc–plateau accretion. Estimating the gain component depends on distinguishing between growth of margins by either accretion of oceanic crust, or juvenile magmatic addition during extension. Distinguishing between these allochthonous and autochthonous models is frequently ambiguous due to difficulties in interpreting the tectonic origin of mafic rocks. We present a detailed geochronological and isotopic study constraining the evolution of the continental margin of northwest South America during 190–113 Ma. Semi-continuous slab rollback resulted in crustal thinning, juvenile magmatism, and ultimately, the removal of continental slivers; negating previous hypotheses that the margin evolved by the accretion of an island arc. However, basic crustal growth estimates, along with comparisons between rocks exposed in Northern Peru and the Northern Andes imply that uneven losses of continental crust occurred along northwest South America for Mesozoic exposures, and that the accretion of the Caribbean Large Igneous Province (CLIP) onto NW South America probably played a crucial role in maintaining and preserving Mesozoic continental crust north of the Huancabamba deflection.

1. Introduction

The nature of trench retreat or advance at the ocean–continent interface is key to understanding crustal growth (Kemp et al., 2009), crustal destruction (Clift and Vannucchi, 2004) and the interplay between both possibilities. Periods of slab rollback are routinely associated with back-arc extension, crustal thinning, separation of continental slivers and juvenile crustal addition (Collins, 2002; Kemp et al., 2009; Mišković and Schaltegger, 2009), whereas slab advance or flat-slab subduction frequently drives compressional deformation, subduction erosion, thickening and ultimately recycling of the crust (Collins, 2002; Gutscher et al., 2000; Jenkins et al., 2002). Several authors (Clift et al., 2009; Scholl and Von Huene, 2007) have demonstrated that the growth of continental crust at continental arcs over long periods is negligible or in decline. Interesting questions include i) how can we distinguish between allochthonous (or exotic terrane accretion) and autochthonous models of continental evolution at subduction zones, ii) how does the volume of new crust formed during attenuation compare with the volumes added by the accretion of oceanic arcs and plateaus, and iii) what processes can facilitate the preservation of new juvenile crust in the geological record?

This study addresses these questions by investigating the mechanisms of crustal growth and preservation that are recorded by crystalline arc rocks within north-western South America, which span a period of ~80 Ma. The Northern Andes are located along a long-lived active margin (since at least 190 Ma), which is interpreted to have evolved by either i) the Cretaceous (140–75 Ma) accretion of allochthonous Mesozoic oceanic and continental terranes (Aspden et al., 1987; Litherland et al., 1994; Toussaint and Restrepo, 1994), or ii) cycles of extension and compression of autochthonous rocks (Nivia et al., 2006; Pratt et al., 2005). Distinguishing between these fundamentally different mechanisms for the construction and preservation of the margin of north-western South America would contribute further to understanding the mechanisms of growth of continental crust along subducted margins.

Recent studies (Cochrane et al., 2014b; Collins et al., 2011; Hawkesworth and Kemp, 2006; Kemp et al., 2006, 2009) traced

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* Corresponding author. Tel.: +44 7506966278.
E-mail addresses: ryan.cochrane@thomsonreuters.com (R. Cochrane), richard.spikings@unige.ch (R. Spikings), gerdes@em.uni-frankfurt.de (A. Gerdes), wilfried.winkler@erdw.ethz.ch (W. Winkler), Alexey.Ulianov@unil.ch (A. Ulianov), andresmora30@googlemail.com (A. Mora), Massimo.Chiaradia@unige.ch (M. Chiaradia).

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processes of magma production within subduction environments by monitoring the long-term Hf (zircon) isotopic variations of magmatic rocks within arcs. This approach improved our understanding of magmatic processes in accretionary orogens, and provided a method for tracking crustal thickening and thinning. The tectonic evolution of some continental margins consisting of autochthonous rocks is dominated by switching between extensional and compressive phases (Collins, 2002). The isotopic composition of these margins should evolve gradually, as the thickness of the crust varies, and the asthenosphere cycles between tectonic exhumation and burial. Margins that evolve by the accretion of oceanic arcs should be characterized by distinct leaps in isotopic composition and crystallization age across terrane sutures (e.g. Öhlander et al., 1993).

We investigate the evolution of the north-western South American margin by integrating i) laser ablation inductively coupled mass spectrometry (LA-ICP-MS) U–Pb (zircon) dates and Hf isotopic compositions of zircon from magmatic rocks, and detrital zircons extracted from meta-sedimentary rocks, and ii) whole rock major oxide, trace element, rare earth element (REE) and Sr–Nd–Pb isotopic analyses of magmatic rocks. These data were collected from suspect continental and oceanic slivers, and are used to distinguish between growth of the continental crust by the addition of oceanic terranes, and in-situ growth driven by alternating periods of extension and compression.

2. Geological setting

A majority of the rocks exposed in the Northern Andes (north of 5°S) formed as a consequence of subduction of Pacific oceanic lithosphere beneath the continental crust of north-western South America. Subduction has been almost continuous beneath Ecuador since ~190 Ma (Cochrane, 2013; Litherland et al., 1994), although it has been interrupted by changing roll-back velocities, and changing plate convergence vectors and terrane accretion (Aspden et al., 1987; Bayona et al., 2006; Pindell and Kennan, 2009; Spikings et al., 2010).

The metamorphic Palaeozoic–Triassic basement of the Eastern Cordillera of Ecuador and Central Cordillera of Colombia, which expose equivalent rock sequences (Fig. 1), was intruded by an I-type, calc-alkaline continental arc between ~190 and 145 Ma (Litherland et al., 1994; Villagómez et al., 2011). Within Ecuador, these batholiths are called the Rosa Florida, Zamora, and Abitagua batholiths and the volcanic arc rocks are grouped within the Misahualli Formation (Litherland et al., 1994; Pratt et al., 2005). Similar Jurassic aged batholiths within Colombia include the Ibague and Segovia batholiths, and volcanic rock sequences within the Saldaña Formation (e.g. Vinasco et al., 2006).

Traversing oceanward (westward) from the Jurassic batholiths and crossing the Cosanga Fault in Ecuador, the Salado Terrane (Litherland et al., 1994) is characterized by interbedded Late Jurassic–Early Cretaceous turbiditic metasedimentary rocks and mafic lavas, and foliated I-type, calc-alkaline batholiths. These rocks are juxtaposed against Palaeozoic–Triassic metamorphosed basement to the west, via the Llanganates Fault, which is referred to as the Loja Terrane (Litherland et al., 1994). Traversing further oceanward, these relatively old basement rocks are faulted against a series of basalts, andesites and meta-turbiditic sequences, which are considered on the basis of geochemical data and field relationships to be either i) an accreted oceanic island arc sequence (the Alao Terrane of Litherland et al., 1994), or ii) an autochthonous series of arc volcanic rock (Nivia et al., 2006; Pratt et al., 2005; Villagomez et al., 2011). Further west, the Alao sequences are buttressed against anastomosed, faulted slivers of mafic–ultramafic rocks, which are collectively defined as the Peltetec Unit and are considered to represent fragments of an obducted ophiolite (Litherland et al., 1994). Quartzites and slates exposed to the west of the Peltetec Fault are interpreted (Litherland et al., 1994; Noble et al., 1997; Pindell and Kennan, 2009) to form part of an allochthonous continental terrane (the Guamote Terrane).

Similar rock sequences and spatial relationships are found along a westward oriented traverse across the Central Cordillera of Colombia (Villagómez et al., 2011). Triassic ortho- and paragneisses of the Cajamarca Complex and poorly studied Palaeozoic metamorphic units crop out to the west of the Ibague Batholith (Villagomez, 2010). These units are truncated along their western margin by the San Jeronimo Fault, which separates them from a series of pillow basalts, andesites, pyroclastic rocks and Albian–Aptian fossil (Gonzáles, 1980) bearing marine sedimentary rocks, which are collectively known as the Quebradagrande Complex (Maya and Gonzales, 1995; Nivia et al., 2006). Continuing westward, the Quebradagrande Complex is faulted against variably metamorphosed ultramafic and mafic igneous rocks. These are exposed in fault-bounded lenses along the Cordillera Central and include the Arquía (e.g. Restrepo and Toussaint, 1976), Jambaló (Bustamante et al., 2011; Orrego et al., 1980) and Barragán (e.g. Bustamante et al., 2012) complexes, among others.

A tectonic model has been proposed (Litherland et al., 1994) for Ecuador which shows these sequences accreting together during a major compressive event at 140–120 Ma. The authors interpret the Alao volcanic sequence and Peltetec unit as oceanic crust, and thus their accretion represents significant addition of mass to the continental crust over a short period of time. Alternatively, Pratt et al. (2005) suggest the same rock sequences within the Eastern Cordillera of Ecuador formed in-situ, because they claim that i) the terrane sutures (Litherland et al., 1994) are intrusive contacts, ii) there are stratigraphic transitions across the previously proposed terrane sutures and iii) both flanks of the Eastern Cordillera of Ecuador have the same structural history along with the ubiquitous presence of blue quartz found both within the siliciclastic sedimentary rocks of the Hollin fm. located within the Sub Andean zone and the Guamote formation on the far western flank of the eastern Cordillera. Any growth of the continental crust within an autochthonous margin (Pratt et al., 2005) would occur by a mechanism that is completely different to exotic terrane accretion. The ability to distinguish between this model and that of accretion of allochthonous terranes is crucial to improve our understanding of how the volume of continental crust along this margin changes with time.

3. Methods

3.1. Whole rock geochemistry and Sr–Nd–Pb isotopes

Sixty-one granitoids and meta-volcanic rocks collected from the Eastern (Ecuador) and Central Cordillera (Colombia) were sampled and chemically analyzed (Table S1). Representative whole rock powders were prepared using an agate mill and major and trace elements were measured using a Philips PW2400 X-Ray Fluorescence (XRF) spectrometer. The NIMN, NIMG, BHVO and SY2 standards were used for quality control. The glass fused disks prepared from XRF analyses were fragmented and mounted for additional analyses of trace and rare earth elements (REE). Measurements were made using a Perkin Elmer ELAN 6100 DRC quadrupole ICP-MS and depending on the expected enrichment within samples, either NIST SRM 610 or 612 fused glasses were used as external standards. The laser settings used for analyses were 10 Hz frequency, 140 mJ energy and 80–120 μm spot size. Blanks were measured for ~90 s, after which the laser was switched on and the signal was measured for 45 s. The Sr or Al_2O_3 concentration (previously determined by XRF) was used as an internal standard. Each sample was ablated 3 times, and average concentrations were calculated offline using LAMTRACE (Jackson, 2008). The uncertainties of 3 spots per sample were <10% for rare earth elements (REE) and <5% for other trace elements.

Twenty-seven volcanic rocks were collected for Sr–Pb–Nd isotopic analyses (Table S1). Approximately 100 mg of whole rock powder was dissolved in 4 ml of concentrated HF and 1 ml of 15 M HNO_3 in closed Teflon vials at 140 °C for seven days. The samples were dried down