Precambrian Research 267 (2015) 285–310

Contents lists available at ScienceDirect

Precambrian Research

journal homepage: www.elsevier.com/locate/precamres

Unraveling crustal growth and reworking processes in complex zircons from orogenic lower-crust: The Proterozoic Putumayo Orogen of Amazonia

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ARTICLE INFO

Article history:
Received 6 March 2015
Received in revised form 3 June 2015
Accepted 23 June 2015
Available online 2 July 2015

Keywords:
U–Pb–Hf–O
Amazonia
Rodinia
Putumayo Orogen
Crustal evolution

ABSTRACT

High-grade basement massifs exposed in the northern Andes and the buried basement of the adjacent Putumayo foreland basin contain a record of Amazonia's involvement in the supercontinent Rodinia. Metasedimentary granulites and orthogneisses, strongly deformed during at least one metamorphic episode dated at ca. 0.99 Ga, provide critical information on the pre-collisional history of the Mesoproterozoic continental margin. Here, new U–Pb, Lu–Hf, Sm–Nd and O isotopic data from outcrop samples of the Garzón and Las Minas Cordilleran basement massifs as well as fragments of drill-core recovered from the Putumayo basin basement are reported. We explore the application of a dual-ICP-MS approach to obtain concurrent U–Pb and Lu–Yb–Hf information on complexly zoned zircon from orogenic lower-crust, and demonstrate its use to retrieve reliable pre-metamorphic information despite possible complexities introduced by mixed-domain ablation and isotopic disturbance of the U–Pb system by thermally induced recrystallization. In combination with $\delta^{18}O$ compositions from the same zircon growth domains, and bulk-rock Nd isotope information, we reconstruct segments of the tectonic and crustal evolution of a long-lived accretionary orogen that developed along the (modern) NW margin of Amazonia during most of the Mesoproterozoic. Inherited zircons in metaigneous samples from the Cordilleran massifs, with protolith crystallization ages in the range from ca. 1.47 to 1.15 Ga, have Hf–O compositions that indicate significant crustal reworking in their source region, but denote a trend of increasing $^{176}Hf/^{177}Hf$ with decreasing age that can be attributed to rejuvenation by progressive addition of radiogenic components during this time interval. Detrital zircons within this same age range found in metasedimentary granulites of the Garzón massif also follow this trend, further supporting previous inferences that their protoliths were deposited in arc-proximal basins with little to no coarse-grained detritus delivered from an older cratonic domain. A shift in orogenic deformation style starting at ~1.15–1.10 Ga, inferred to be associated with the accretion of fringing-arc terranes against the continental margin, triggered an early amphibolite-grade metamorphic episode; this was accompanied by pervasive partial melting and migmatite development in fertile metasedimentary units and is interpreted to be responsible for enhanced crustal reworking evidenced from the shallowing of $^{176}Hf/^{177}Hf$ vs. age trends in detrital and metamorphic zircons from the Garzón and Las Minas massifs. Convergent tectonism along the Putumayo margin came to an end during the final incorporation of Amazonia to the core of the Rodinia supercontinent, possibly during collision against the Sveconorwegian segment of Baltica at 0.99 Ga. Although the position and role of Amazonia within Rodinia remains controversial, the new Nd and Hf isotope data provide additional evidence to link the

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http://dx.doi.org/10.1016/j.precamres.2015.06.014

evolution of this orogenic segment with the basement of Oaxaquia, as well as continue to draw fundamental differences with the timing and nature of the tectonic processes associated with the development of the Sunsás-Aguapeí Orogen of SW Amazonia.

1. Introduction

Zircon isotope geochemistry is fundamental to understanding the formation and differentiation of continental crust on Earth (e.g., Patchett et al., 1981; Valley et al., 2005; Belousova et al., 2010; Dhuime et al., 2012; Cawood et al., 2013; Hawkesworth et al., 2013), but becomes increasingly challenging when applied to fragments of strongly modified continental lithosphere that have undergone poly-phase tectonic-thermal histories and pervasive metamorphic recrystallization (e.g., Whitehouse et al., 1999; Zeh et al., 2007; Kemp et al., 2009a). High-temperature crustal reworking has the potential to induce multi-phase growth histories within single-zircon crystals, which complicate the age assignment to complementary geochemical indicators. However, despite their possible textural complexities, reliable primary geochronologic and geochemical information can still be determined from reworked zircon crystals owing to the extremely slow volume-diffusion properties of U–Pb–Hf–O in this mineral (Cherniak et al., 1997; Watson and Cherniak, 1997; Cherniak and Watson, 2000, 2003; Peck et al., 2003; Page et al., 2007; Bowman et al., 2011). Therefore, the continuous improvement in spatial resolution, precision, and accuracy of in situ radioisotopic methods for studying minerals with multi-phase growth histories continues not only to revolutionize our understanding of the geochemistry of zircon, but also to provide unprecedented insights into crust-forming and reworking processes at increasingly finer resolutions in strongly deformed orogenic crust.

Continental collision tectonism has been inferred to play a crucial role in the shaping and stabilization of Earth's preserved continental lithosphere (Hawkesworth et al., 2009), and exerted a primary control on the global detrital-zircon geochronologic pattern of ancient and modern sediments (Campbell and Allen, 2008; Voice et al., 2011; Spencer et al., 2015). If major peaks and troughs in the global detrital-zircon age distribution are indeed an artifact of selective preservation instead of arising from changes in fundamental crust-generating processes (e.g., Hawkesworth et al., 2009, 2013; Condie et al., 2011), then further scrutinizing the geochemical and isotopic record of major pre-collisional orogens through time should provide fundamental insights into understanding the composition of Earth's preserved continental crust (Rudnick and Gao, 2014). Furthermore, in addition to providing clues for evaluating the mechanisms responsible for long-term crustal differentiation, linkages between isotopic compositions and particular tectonic processes can be used to impose robust temporal and geodynamic constraints on the developmental history of complex and/or poorly represented orogens. This information plays a critical role in the study of processes associated with the supercontinent cycle, as any proposed topological model for the global agglomeration of continental masses has to satisfy the temporal, tectonic, and structural constrains dictated by the geological evolution of lithospheric fragments formed prior, during and after continental collision (e.g., Dalziel, 1991; Pisarevsky et al., 2003; Bogdanova et al., 2008; Li et al., 2008, 2009; Evans and Mitchell, 2011).

The recently defined Putumayo Orogen of northern South America holds critical information for understanding the participation of Amazonia in the assembly of the supercontinent Rodinia (Cordani et al., 2009; Ibanez-Mejia et al., 2011), and the role that Mesoproterozoic accretionary orogenesis had in the growth of one of Earth's largest Precambrian landmasses (Cordani and Teixeira, 2007). In order to elucidate the Proterozoic crustal development history of the NW Amazon Craton and to provide a more comprehensive understanding of its role within Mesoproterozoic tectonics, we applied a combination of texturally resolved U–Pb, Lu–Hf and O isotopic techniques to investigate the record of complex polycyclic meta-igneous and meta-sedimentary zircon crystals from high-grade rocks of the Putumayo Orogen. These results, complemented by bulk-rock Nd isotopic data, are used to reconstruct segments of a long-lived history of Mesoproterozoic convergent tectonism along this segment of the Amazonian margin, as well as draw strong geochronologic and isotopic correlations between the now dismembered fragments that have been proposed to once make an integral part of this orogen. In an effort to assign the most reliable U–Pb ages to each Lu–Hf isotopic composition, a critical step toward accurately interpreting such data, U–Pb and Lu–Yb–Hf isotopic data were simultaneously acquired from the same ablated zircon volumes by a laser ablation dual-ICP-MS approach calibrated at the University of Arizona during the course of this study. We show that this analytical strategy offers the possibility to study a variety of processes such as igneous and metamorphic petrogenesis, detrital-zircon provenance, and paleogeographic development of orogenic crustal fragments where complex zircon growth histories are the end result of their poly-phase tectonothermal evolutions.

2. Tectonic context of the Putumayo Orogen and sampling locations

The Amazon Craton, commonly referred to as Amazonia (Fig. 1A), is thought to be one of the major Precambrian continental nuclei that occupied the core of the Rodinia Supercontinent during the late Meso- to early Neoproterozoic (Hoffman, 1991; Li et al., 2008; Cordani et al., 2009). The occurrence of a late Mesoproterozoic collisional metamorphic belt in the lowlands of eastern Bolivia and western Brazil, the Sunsás-Aguapeí belt, has traditionally provided support for this idea (Litherland and Bloomfield, 1981; Teixeira et al., 1989, 2010). Although paleogeographic, geochronologic and paleomagnetic evidence indicate the Grenville margin of Laurentia as a feasible hypothesis for a conjugate collisional margin to the Sunsás, debate still persists over the specific segment of Laurentia against which Amazonia collided (Sadowski and Bettencourt, 1996; Tohver et al., 2002, 2004, 2006; Loewy et al., 2003; D'Agrella-Filho et al., 2008; Gower et al., 2008; Johansson, 2009, 2014). A possible northern continuation of the Sunsás belt along the fringe of the Amazon Craton has been contentious, as fragments of late Mesoproterozoic crust east of the Andean deformation front in modern-day Peru, Ecuador, and Colombia had not been previously recognized (Fig. 1A). There is now, however, growing geological and geochronological evidence that supports the existence of a collisional Stenian–Tonian orogenic belt hidden under the north Andean foreland basins in northwestern South America, herein called the Putumayo Orogen, which provides important new constraints for the role of Amazonia prior and during the assembly of the Rodinia supercontinent.