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Short episodes of crust generation during protracted accretionary processes: Evidence from Central Asian Orogenic Belt, NW China

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ABSTRACT

Accretionary orogens are major sites of generation of continental crust but the spatial and temporal distribution of crust generation within individual orogens remains poorly constrained. Paleozoic (∼540–270 Ma) granitic rocks from the Alati, Junggar and Chinese Tianshan segments of the Central Asian Orogenic Belt (CAOB) have markedly bimodal age frequency distributions with peaks of ages at ∼400 Ma and 280 Ma for the Altai segment, and ∼430 Ma and 300 Ma for the Junggar and Chinese Tianshan segments. Most of the magma was generated in short time intervals (∼20–40 Ma), and variations in magma volumes and in Nd–Hf isotope ratios are taken to reflect variable rates of new crust generation within a long-lived convergent plate setting. The Junggar segment is characterized by high and uniform Nd–Hf isotope ratios ($\varepsilon_{Nd}(t) = +5$ to $+8$; zircon $\varepsilon_{Hf}(t) = +10$ to $+16$) and it appears to have formed in an intra-oceanic arc system. In the Altai and Chinese Tianshan segments, the Nd–Hf isotope ratios ($\varepsilon_{Nd}(t) = -7$ to $+8$; zircon $\varepsilon_{Hf}(t) = -16$ to $+16$) are lower, although they increase with decreasing age of the rock units. The introduction of a juvenile component into the Chinese Tianshan and Altai granitic rocks appears to have occurred in continental arc settings and it reflects a progressive reduction in the contributions from old continental lower crust and lithospheric mantle. Within the long-lived convergent margin setting (over ∼200 Ma), higher volumes of magma, and greater contributions of juvenile material, were typically emplaced over short time intervals of ∼20–40 Ma. These intervals were associated with higher Nb/La ratios, coupled with lower La/Yb ratios, in both the mafic and granitic rocks, and these episodes of increased magmatism from intraplate-like sources are therefore thought to have been in response to lithospheric extension. The trace element and Nd–Hf isotope data, in combination with estimates of granitic magma volumes, highlight that crust generation rates are strongly non-uniform within long-lived accretionary orogens. The estimated crust generation rates range from ∼0.1 to ∼40 km^3/km/Ma for the Paleozoic record of the CAOB, and only comparatively short (20–40 Ma) periods of elevated magmatic activity had rates similar to those for modern intra-oceanic and continental arcs.

1. Introduction

Accretionary orogens form along convergent plate margins and they are major sites of juvenile crust production (Cawood et al., 2013, and references therein). They are complex zones with long histories of lithospheric interaction resulting in the generation of new crust, the recycling of material to the mantle through subduction erosion and sediment subduction, and of lithospheric reworking during tectonothermal events (e.g. Scholl and von Huene, 2007; Stern, 2011; Cawood et al., 2013 and references therein). There is increasing evidence that continental growth takes place in different ways in different accretionary orogens, including outward growth of juvenile magmatic arcs, and mantle input during extensional, back-arc rifting episodes (Sengör et al., 1993; Davidson and Arculus, 2006; Cawood et al., 2009; Kemp et al., 2009). In many cases

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the implication is that juvenile crust generation is associated with the extensional stage of accretionary orogens, whereas both crustal reworking and recycling are associated with compressional stages (Kemp et al., 2009; Collins et al., 2011).

The Central Asian Orogenic Belt (CAOB; also named the Altaids, Fig. 1a) extends from the Urals in the west, to the Okhotsk Sea along the eastern Russian coast, and it represents a major pulse of Phanerozoic continental growth (Sengör et al., 1993; Jahn, 2004; Kröner et al., 2007; Wilhem et al., 2012). This paper focuses on the Chinese Tianshan, the Junggar and the Altai segments of the North Xinjiang region, and each provides a record of igneous activity throughout most of the Paleozoic. The Chinese Tianshan segment is divided into North, Central, and South Tianshan and the Yili Block (Fig. 1c). We present a synthesis of over 2100 whole rock trace element analyses and some 860 Nd isotope and almost 4000 zircon Hf isotope analyses from granitic and mafic rocks in these temporally overlapping accretionary systems. These are combined with estimates of the outcrop areas of granitic rocks of different ages in the different segments to evaluate changes in magma volumes, and by implication provide a proxy of magma productivity. Magma productivity is highly variable during the overall history of long-lived accretionary orogens, and in this contribution we use isotope and trace element data (1) to evaluate the amount and nature of juvenile contributions to granitic magmas at different stages, and (2) to link changes in tectonic activity to crust production in the North Xinjiang segment of the CAOB. The data highlight that most of the magma, and more than 90% of the juvenile component in the North Xinjiang segments, as evaluated from the surface areas of different granites, was emplaced over short time intervals. This has implications for crustal growth in accretionary orogens worldwide.

2. Geological background and Paleozoic magmatism

The CAOB is one of the largest accretionary orogenic belts in the world, and it encompasses an area roughly 5000 km (E–W) in length and up to 800 km (N–S) in width (Sengör et al., 1993; Windley et al., 2007; Kröner et al., 2014) (Fig. 1a). It has a long and complex tectonic evolution from at least ∼1.0 Ga, focused in the northern part of the orogen (Khain et al., 2002), to ∼250 Ma (Xiao et al., 2003), and associated with the growth and consumption of the Paleo-Asian Ocean. It is characterized by accretion of a number of terranes including island arcs, ophiolites, accretionary prisms, and possibly some microcontinents (Kröner et al., 2007; Windley et al., 2007). The outstanding feature of the CAOB is the vast expanse of granitic and volcanic rocks that are characterized by positive $\varepsilon_{\mathrm{Nd}}(t)$ and young T_{DM} model ages, representing the world's largest region of continental crust generation during the Phanerozoic (Han et al., 1997; Wu et al., 2002; Chen and Jahn, 2004; Jahn, 2004). However, recent Nd–Hf isotopic data for felsic magmatic rocks have been used to argue that the volume of new crust has been grossly over estimated in the CAOB, which would not support models invoking unusually high crust generation rates during its accretionary history (Kröner et al., 2014).

The southern part of the CAOB in the North Xinjiang region of China extends about 800 km across strike, and from north to south it consists of three broadly contemporaneous accretionary assemblages: the Altai, Junggar and Chinese Tianshan segments (Fig. 1b–c). These accretionary assemblages are thought to have formed through successive subduction and accretion events along the margins of the Paleo-Asian Ocean that lay between the Siberian and Tarim cratons (Xiao et al., 2003; Wilhem et al., 2012). The Tarim Craton accreted to the Yili–Central Tianshan block on the southern margin of the CAOB, primarily in the late Carboniferous, following northward closure of the Paleo-Asian Ocean (and its branch oceans). The timing of the closure of the ocean is constrained by ca. 320 Ma suture-related eclogite overlain nonconformably by undeformed young Carboniferous limestone at Kyrgyz in the South Tianshan (Hegner et al., 2010). Consequently, post-290 Ma magmatic rocks are significantly younger than the age of accretion/collision (Kröner et al., 2014).

The Chinese segment of the Altai consists of variably deformed and metamorphosed Neoproterozoic to Paleozoic sedimentary and volcanic rocks (Sun et al., 2008). The Altai segment is separated from the Junggar segment by the Erqis suture (Fig. 1c), which contains Devonian to early Carboniferous ophiolitic rocks. Boninites, magnesian andesites, adakites, high-Ti basalts and Nb-rich basalts occur in tectonic blocks along this suture zone (Shen et al., 2014).

Voluminous Paleozoic granitic intrusions, with ages ranging from 500 Ma to 250 Ma (Fig. 2a), occur throughout the Altai segment and account for more than 40% of the exposed rocks (Yuan et al., 2007). The granitic intrusions include metaluminous I-type, peraluminous S-type, and geochemically distinctive A-type plutons. I- and S-type intrusions were mainly emplaced in the early Paleozoic, with minor I-type intrusions emplaced in the late Paleozoic, whereas most A-type intrusions are younger and were emplaced in the early Permian (Fig. 1e). Most granitic rocks from the Altai segment are calcic and calc-alkalic (Frost et al., 2001) (Supplemental Fig. 1). The outcrop area, and by inference the volume of the granitic intrusions in the Altai segment declines with decreasing age of emplacement after the peak at about 400 Ma (Fig. 2).

The Junggar segment of the CAOB is characterized by Paleozoic ophiolitic mélanges and volcanic rocks and it is divided into eastern and western parts separated by the Junggar Basin. Geochemical and isotopic evidence are consistent with the formation of the Junggar segment in an intraoceanic arc setting (Zheng et al., 2007). The basement to the Junggar Basin consists of mainly late Paleozoic volcanic rocks with minor shales and tuffs (Zheng et al., 2007). The western Junggar region also consists of Paleozoic volcanic and sedimentary assemblages intruded by granitic rocks. No significantly older basement has been documented in the western Junggar region.

U–Pb age dating of zircon from the granitic intrusions within the Junggar segment indicates that most were emplaced during the late Carboniferous and early Permian, with a minority in the Silurian (Fig. 2a). Geochemically, these intrusions consist of A-type and subordinate I-type granites, and most granitic rocks are calc–alkalic and alkalic–calcic (Frost et al., 2001) (Supplemental Fig. 1). In contrast to the Altai granites, the outcrop area of these Junggar granitic intrusions increases with decreasing emplacement age (Fig. 1e).

The Tianshan segment extends east–west for more than 2400 km from Uzbekistan to Xinjiang in China (Gao et al., 2009) (Fig. 1b–c). It represents an extended belt of Paleozoic magmatism that was associated with subduction beneath lithosphere containing blocks of Precambrian basement formed in the early Neoproterozoic. The Chinese Tianshan is dominated by Paleozoic S-, I- and A-type granitic intrusions, metasedimentary rocks and minor mafic rocks (Gao et al., 2009). Most of the granitic rocks are calc–alkalic and alkalic–calcic (Supplemental Fig. 1). These rock types and the geochemical characteristics of the Chinese Tianshan granitic intrusions are similar to those of the Altai segment, and they were emplaced from 500 Ma to 270 Ma, also with a bimodal distribution of ages (Figs. 1d; 2a). Most granitic intrusions were emplaced during two intervals at 310–290 Ma and 470–430 Ma (Fig. 2a), and the outcrop area of rocks associated with the younger pulse is greater than that for the older phase (Fig. 2a).

3. Age frequency distributions and magma volumes

It can be difficult to evaluate the extent to which the frequency distribution of U–Pb zircon ages reflects variations in the