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GR focus review

The building blocks of continental crust: Evidence for a major change in the tectonic setting of continental growth at the end of the Archean

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A B S T R A C T

Oceanic arcs are commonly cited as primary building blocks of continents, yet modern oceanic arcs are mostly subducted. Also, lithosphere buoyancy considerations show that oceanic arcs (even those with a felsic component) should readily subduct. With the exception of the Arabian–Nubian orogen, terranes in post-Archean accretionary orogens comprise <10% of accreted oceanic arcs, whereas continental arcs compose 40–80% of these orogens. Nd and Hf isotopic data suggest that accretionary orogens include 40–65% juvenile crustal components, with most of these (>50%) produced in continental arcs.

Felsic igneous rocks in oceanic arcs are depleted in incompatible elements compared to average continental crust and to felsic igneous rocks from continental arcs. They have lower Th/Yb, Nb/Yb, Sr/Y and La/Yb ratios, reflecting shallow mantle sources in which garnet did not exist in the restite during melting. The bottom line of these geochemical differences is that post-Archean continental crust does not begin life in oceanic arcs. On the other hand, the remarkable similarity of incompatible element distributions in granitoids and felsic volcanics from continental arcs is consistent with continental crust being produced in continental arcs.

During the Archean, however, oceanic arcs may have been thicker due to higher degrees of melting in the mantle, and oceanic lithosphere would be more buoyant. These arcs may have accreted to each other and to oceanic plateaus, a process that eventually led to the production of Archean continental crust. After the Archean, oceanic crust was thinner due to cooling of the mantle and less melt production at ocean ridges, hence, oceanic lithosphere is more subductable. Widespread propagation of plate tectonics in the late Archean may have led not only to rapid production of continental crust, but to a change in the primary site of production of continental crust, from accreted oceanic arcs and oceanic plateaus in the Archean to primarily continental arcs thereafter.

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1. Introduction

Continents are often thought to be the products of accretion of oceanic arcs (Kusky and Polat, 1999; Stern, 2008; Xiao et al., 2010a). Taylor (1967) was among the first to show that the bulk composition of continents is similar to andesite, and because andesite was assumed to represent the composition of oceanic arcs, the simplest way to form continents is by the amalgamation of oceanic arcs. We now know, however, that oceanic arcs are not andesitic in composition, but basaltic (or in a few cases basaltic andesite) (DeBari and Sleep, 1991), and their composition must be changed to make felsic continental crust. This is necessary even for the Izu-Bonin arc, which may have a tonalitic mid-crustal layer based on seismic velocity distribution (Kodaira et al., 2007). Just how oceanic arc crust is changed has been the subject of numerous studies, and almost always necessitates recycling of mafic and ultramafic restites into the mantle by some process of delamination (DeBari and Sleep, 1991; Clift et al., 2005). In addition, it requires a significant incompatible-element enriched mantle source (Pearcy et al., 1990; DeBari and Sleep, 1991). This all presupposes that oceanic arcs are indeed the building blocks of continents, an assumption which has not been adequately evaluated. A related question is that of how continents formed in both the early and late Archean and whether the process involved the same mechanism as after the Archean.

It is these questions that are addressed in this study, particularly focusing on the role of oceanic arcs in continental growth by accretion and by production of felsic magmas in oceanic arcs. Because the contrasting roles of oceanic and continental arcs are important in continental evolution, we first need to distinguish between these two types of arcs. The most obvious distinction is that oceanic arcs form on oceanic lithosphere and continental arcs form on continental lithosphere. However, in practice this distinction may not be useful since the bottoms of arc successions are mostly not exposed at the surface. Hence, we must rely on indirect evidence such Nd, Hf and other radiogenic isotopic ratios that are sensitive to the ages and composition of the basement upon which arcs are constructed. Both xenoliths and zircon xenocrysts, which are common in many continental arc igneous rocks, are critical in applying isotopic tracers to characterize magmatic sources. Complicating the distinction between arcs is the fact that oceanic arcs can transition into continental arcs as, for instance, occurs in the eastern Aleutian Islands today (Fliedner and Klemperer, 2000). In a few instances, such as the Peninsular Range batholith in southern California (Lee et al., 2007) and two Paleozoic arcs in Ireland (Draut et al., 2009), oceanic arcs may accrete to the continents where they thicken and evolve into continental arcs within 10–20 Ma.

The term "island arc" is widely used in the literature to refer to arcs constructed on oceanic lithosphere. However, as exemplified by continental margin arcs such as Japan and the Sunda arc in Indonesia, both of which are island arcs, this is not always the case. Island arcs may form on either oceanic or continental lithosphere. To avoid this ambiguity, we use the terms oceanic and continental arc to refer to arcs built on oceanic and continental lithosphere, respectively, and avoid the term island arc.

2. Data input and uncertainties

To evaluate the question of how important oceanic arcs are in continental growth, it is necessary to identify the tectonic settings of terranes accreted to continents. Most terranes involve more than one tectonic setting and tectonic settings can change with time as plate scenarios evolve. To identify ancient tectonic settings in this study, emphasis is given to petrotectonic assemblages including their geochemistry, and when available, to the abundances and compositions of pre-collisional plutons. Because syn- and post-collisional plutons almost always involve varying amounts of older sources from both the underlying craton and older accreted terranes, they cannot be considered as pristine components of accreted terranes. Rock volume proportions are estimated from geologic maps and measured stratigraphic sections (Condie, 1993). Distinction between juvenile and reworked crustal components uses results from Nd and Hf isotopic studies (Condie and Chomiak, 1996; Condie, 2007; 2008; Condie et al., 2011). One of the major uncertainties is the volume of accreted terranes. We have used published seismic sections from the LITHOPROBE studies in Canada and the COCORP results in the United States to constrain the shapes and sizes of accreted terranes at depth in Laurentia (Hammer and Clowes, 2004; Cook and Erdmer, 2005; Cawood et al., 2009). In Proterozoic terranes of the Southwest United States, terrane volumes are estimated from surface exposure distributions and seismically determined crustal thicknesses (Levander et al., 2011). In the Arabian–Nubian shield, an assumed average crustal thickness of 38 km is used to calculate terrane volumes (Mooney et al., 1985; Stern and Johnson, 2010). Crustal thicknesses in the Central Asian orogen are estimated from data in Zorin (1999) and Makarov et al. (2010) (and references therein). More details of our methods and associated uncertainties are described in Condie and Chomiak, 1996; Condie, 2007; 2008; and Condie et al., 2011. Over the years, numerous investigators have shared unpublished data with us to improve the reliability of our estimates. Results for this study are compiled in Appendix 1 and are shown graphically in Fig. 1.

Chemical compositions are from published data in our continually updated database of specific rock types, examples of which have been published from time to time (Condie, 1993; 1994; Condie and Chomiak, 1996; Condie, 2008). Uncertainties of element concentrations used in our terrane analysis are also given in these references. Estimating the juvenile crustal input into terranes is always a challenge. We have made use of whole-rock Nd and zircon Hf isotopic databases compiled from published data (Condie, 1998; Condie, 2007; 2008; Wang et al., 2009; Belousova et al., 2010; Condie et al., 2011 and references cited therein). εHf in zircons varies significantly and reflects the proportion of recycled zircons in igneous rocks. If for instance, εHf > +5 is assumed to represent juvenile additions, the juvenile component can range from as low as 30% to more than 50% in continental arcs (Mueller et al., 2008; Sun et al., 2008; Kemp et al., 2009; Miskovic and Schaltegger, 2009; Ravikant et al., 2009; Belousova et al., 2010). We have used combined data from

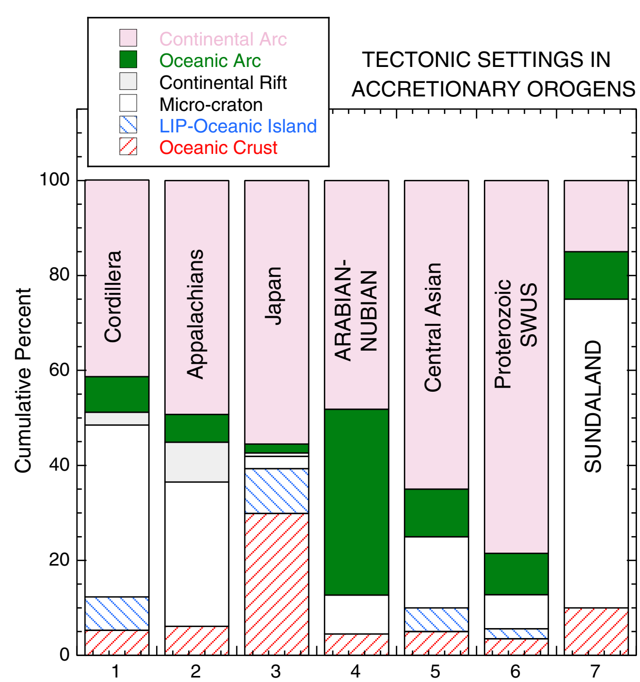

Fig. 1. Estimated volume distribution of tectonic settings in accretionary orogens. Uncertainties ≤20%. See Appendix 1 for data.