Earth and Planetary Science Letters 461 (2017) 85–95

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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Episodic nature of continental arc activity since 750 Ma: A global compilation

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ARTICLE INFO

Article history:
Received 15 October 2016
Received in revised form 3 December 2016
Accepted 27 December 2016
Available online xxxx
Editor: A. Yin

Keywords:
continental arcs
episodicity
plate tectonics
long-term climate

ABSTRACT

Continental arcs have been recently hypothesized to outflux large amounts of CO_2 compared to island arcs so that global flare-ups in continental arc magmatism might drive long-term greenhouse events. Quantitative testing of this hypothesis, however, has been limited by the lack of detailed studies on the spatial distribution of continental arcs through time. Here, we compile a worldwide database of geological maps and associated literature to delineate the surface exposure of granitoid plutons, allowing reconstruction of how the surface area addition rate of granitoids and the length of continental arcs have varied since 750 Ma. These results were integrated into an ArcGIS framework and plate reconstruction models. We find that the spatial extent of continental arcs is episodic with time and broadly matches the detrital zircon age record. Most vigorous arc magmatism occurred during the 670–480 Ma and the 250–50 Ma when major greenhouse events are recognized. Low continental arc activity characterized most of the Cryogenian, middle–late Paleozoic, and Cenozoic when climate was cold. Our results indicate that plate tectonics is not steady, with fluctuations in the nature of subduction zones possibly related in time to the assembly and dispersal of continents. Our results corroborate the hypothesis that variations in continental arc activity may play a first order role in driving long-term climate change. The dataset presented here provides a quantitative basis for upscaling continental arc processes to explore their effects on mountain building, climate, and crustal growth on a global scale.

1. Introduction

Subduction zone volcanism plays an important role in shaping the evolution of Earth's surface. Island arcs, such as the Marianas and Izu–Bonin arcs in the western Pacific, form where an oceanic plate subducts beneath another oceanic plate. Continental arcs, such as the present-day Andes or Cretaceous North American Cordilleran arcs, form when oceanic plates subduct beneath continental plates (Fig. 1a). Because of greater crustal thickness at continental arcs, magmatic differentiation is more extensive in continental arcs than in island arcs, which are thin; continental arcs thus play an important role in the formation of felsic continental crust (e.g. Lee et al., 2007; Lee and Bachman, 2014). The thick crust of continental arcs also results in high elevations, making continental arcs one of the most important environments for mountain building, which in turn influences weathering, atmospheric circulation and the hydrologic cycle (Lee et al., 2015). Continental arcs may also play an important role in long-term climate variability due to the possibility that continental arc volcanoes release more CO_2 than island arc volcanoes as a result of magmatic interaction with ancient crustal carbonates stored in the continental upper plate (Fig. 1b) (Lee et al., 2013; Lee and Lackey, 2015; McKenzie et al., 2016).

To what extent the surface geology and environment of Earth is modulated by the rise and fall of continental arcs is uncertain. Has the length of continental arcs varied with time, and if so, what controls the global nature of subduction zones? Attempts have been made to quantify continental arc activity or continental crust formation using large databases of detrital zircon ages (e.g. Voice et al., 2011; Condie and Kröner, 2013; Roberts and Spencer, 2015; Paterson and Ducea, 2015). These observations suggest that global continental arc activity is not continuous, but is instead episodic, with recent investigators suggesting a correlation between continental arc activity and greenhouse conditions based solely on detrital zircon data (McKenzie et al., 2016). However, some disadvantages of detrital zircon studies are the lack of the direct geologic context or spatial information of arcs. For these reasons, we present here an independent and more direct constraint on continental arc activity by compiling the distribution of

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http://dx.doi.org/10.1016/j.epsl.2016.12.044
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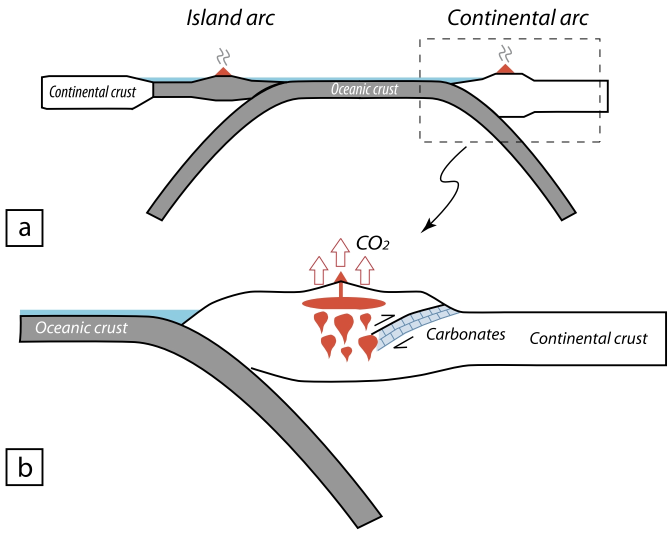

Fig. 1. (a) Cartoon of island and continental arcs; (b) A continental arc showing how the interaction of magmas with carbonates in the upper plate can enhance CO_2 degassing.

continental arcs through space and time using a worldwide set of geologic maps and related literature. We then synthesize the data with plate reconstruction models to develop a geologic history of continental arcs since the Neoproterozoic.

2. Methods

Geologic maps (1:5,000,000 to 1:10,000,000) of Eurasia, North and South America, Africa, Australia, and Antarctica (e.g. Reed et al., 2005; Ren et al., 2013) were used to compile the present-day surface area of felsic-intermediate plutonic rocks (granitoids).

We have assumed that felsic magmas, such as granitoids, most likely represent continental arcs for the following reasons. Cawood et al. (2013) suggested that the volumes of subduction-related magmas make up more than 90% of all volcanism, not including mid-ocean ridge related magmatism. In particular, Lee and Bachmann (2014) showed that felsic (intermediate) magmas are far more abundant in continental arcs than in island arcs, hence we have assumed that the majority of granitoids are formed in the continental arcs. We have, however, excluded the following large plutonic belts where geologic context indicates they are not of continental arc origin: the granitoids associated with the Siberian Traps Large Igneous Province (Ivanov et al., 2013), the A-type granitoids in the Mongolia–Transbaikalian Belt (Jahn et al., 2009), the collision-related Cenozoic granites in the European Alps and Tibet, and the granitic batholiths belonging to the Talkeetna and Kohistan island arc sections (Jagoutz and Kelemen, 2015). Surface areas were extracted using ArcGIS software when shapefiles were available. Otherwise, maps were scanned into high-resolution raster images and processed using ImageJ software (www.imagej.nih.gov). To gauge the productivity of granitoids and continental arc activity, surface area addition rate (km^2/Myr) was calculated by dividing the surface area of granitoids generated within a geological interval by the time duration of that interval.

In addition to calculating the surface area addition rate of granitoids, we also reconstructed the linear lengths of continental arcs based on the geology interpreted from literatures as well as the extrapolation between plutonic surface exposures. We then compiled a global history of continental arcs and restored their positions on paleomaps using plate reconstruction models (Scotese, 2016; Li et al., 2008) in GPlates software (Gurnis et al., 2012). Compiled information on the durations and lengths of continental arcs, error estimate, and a complete list of literature and geologic maps used in this study can be found in the Supplementary Materials.

3. Results

3.1. Continental arcs through space and time

The global history of continental arcs is shown in Fig. 2 and Fig. 3. Two types of continental arcs are differentiated. External arcs (shown as red curves in Fig. 3) are the continental arcs developed along the periphery of a supercontinent. External arcs (shown as purple curves in Fig. 3) are the ones developed internal to an assembling supercontinent, which are usually terminated with continent–continent (or continental terrane) collision. The two types are similar to the classification of accretionary orogen previously proposed (e.g. Murphy et al., 2011).

From 750 Ma to the Early Cryogenian, few continental arcs were active and the length of continental arcs was low (Fig. 3a). From the Late Cryogenian to Late Ediacaran (Fig. 3b), during the final breakup of the Rodinia supercontinent and the formation of the Gondwana supercontinent, Pan-African arcs (e.g. Damara–Kuunga, East African) and the Avalonia–Cadomian arcs became active (e.g. Kröner and Stern, 2004; Linnemann et al., 2008). From the Late Ediacaran to Early Cambrian (Fig. 3b–c), coinciding in time with the late stage of the Pan-African arcs, subduction along the Proto-Pacific margin of Gondwana commenced: for example, the Ross arc in Antarctica, the Delamerian arc in Australia, and the Pampeanas–Famatinian arc in South America (Goodge, 2007; Cawood and Buchan, 2007; Rapela et al., 1998). Studies have also suggested that most of the Proto-Tethyan margin of northern Gondwana was active at the same time (Kusky et al., 2003; Zhu et al., 2012). Afterwards, continental arcs waned during the Ordovician and Silurian (Fig. 3d). From the Ordovician to Devonian (Fig. 3d–e), closure of the Iapetus and Rheic Oceans between Baltica, Laurentia, and Gondwana generated the Variscan and Appalachian continental arcs (e.g. Nance and Linnemann, 2008; van Staal et al., 2009). From the Carboniferous to Early Triassic (Fig. 3f–h), diachronous closure of Paleo-Asian oceans, which led to the final assembly of the Pangea supercontinent, gave rise to several Paleo-Asian arcs (e.g. Uralian, Altai, Kazakhstan Balkhash–Yili, Solonker) (e.g. Windley et al., 2007). During the Permian and Early Triassic (Fig. 3g–h), circum-Pacific subduction commenced along the western and northeastern margins of Pangea, resulting in numerous continental arcs: the western Pacific arcs in Asia, the Cordilleran arcs in North and South America, and the Antarctic Peninsula arc (e.g. Metcalfe, 2011; Dickinson, 2004; Ramos and Kay, 2006). During the Mesozoic–Paleocene (Fig. 3h–j), these circum-Pacific arcs dominated global continental arc activity, reaching their longest extents in the Late Cretaceous. Several Tethyan arcs were also active during the same period (e.g. Yin and Harrison, 2000). In the Cenozoic (Fig. 3k–l), the Gangdese and Iran–Turkey arcs shut down with the progressive closure of the Neo-Tethyan Ocean from the Himalaya to the Caucasus (Zhu et al., 2015; Yin, 2010). Many of the circum-Pacific continental arcs also terminated in the Cenozoic. Trench retreat resulted in western Pacific continental arcs transitioning into island arc systems (e.g., Marianas, Izu–Bonin) (Ishizuka et al., 2014). Arc volcanism in western North America waned due to the onset of the flat subduction and collision of the Pacific–Farallon ridge (Dickinson, 2004).

Fig. 4(a–d) summaries geological events and the compiled results of this study. There are two periods of time since 750 Ma when the lengths of continental arcs were high (Fig. 4d). The first period is during the Late Cryogenian and Cambrian (~670–480 Ma), defined by the Pan-African and peri-Gondwana continental arcs. The second period was in the Mesozoic–early Paleogene (~250–50 Ma), defined by the Paleo-Asian arcs, Tethyan arcs, and circum-Pacific continental arcs. The global lengths of continental arcs were low from the Late Tonian to Early Cryogenian (750 Ma–680 Ma), during most of the Paleozoic (~470–250 Ma),