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Coupled magmatism–erosion in continental arcs: Reconstructing the history of the Cretaceous Peninsular Ranges batholith, southern California through detrital hornblende barometry in forearc sediments

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A B S T R A C T

Continental magmatic arcs are characterized by voluminous flare-ups accompanied by rapid arc unroofing and sedimentation in the forearc basin. Such magmatism and erosion may be dynamically linked and influence the long-term evolution of crustal thickness. To evaluate these effects, we conducted a case study in the Peninsular Ranges batholith (PRB) in southern California, where mid-Late Cretaceous (125–75 Ma) emplacement of felsic plutons coincided with a major pulse of arc-derived sediments into the adjacent forearc basin. We compiled zircon U–Pb ages in the PRB plutons and estimated magmatic addition rates from exposed areas of plutons with different ages. To obtain erosion rates, sandstone samples of known depositional age from the PRB forearc basin were investigated. Major element compositions of detrital hornblendes were determined by electron probe microanalysis and used to calculate emplacement depths of eroded plutons using Al-in-hornblende barometry. These results were combined with laser ablation ICPMS based U–Pb ages of accompanying detrital zircons to estimate the integrated erosion rate by dividing the detrital hornblende emplacement depth by the lag time between peak detrital zircon age and depositional age. Both magmatic addition and erosion rates are between 0.1–2 km/Myr. Magmatic addition peaked at 100–90 Ma, followed by a long, protracted period of erosion between 90–50 Ma. Mass balance and isostatic modeling suggests that due to high magmatic influx, more than 30 km integrated crustal growth and 5 km elevation increase was achieved shortly after peak magmatism. The data and models suggest that erosion was driven by magma-induced crustal thickening and subsequent surface uplift, with an erosional response time of 3–6 Myr. Prolonged erosion after the cessation of magmatism resulted in gradual smoothing of the topography and significant removal of the excess crustal thickness by late Eocene time. The short erosional response times inferred from this study suggest that erosion and magmatism are intimately linked, begging the question of whether the thermal state, metamorphism and rheology of crust in continental arcs is controlled in part by the interplay between erosion and magmatism. We speculate that syn-magmatic erosion, through its effects on the thermal structure of the crust, may also play a role in modulating the depth of pluton emplacement.

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1. Introduction

Continental crust is formed in continental arcs through magmatic addition and differentiation, the former derived from partial melting of the mantle or crust and the latter giving rise to the evolved geochemical signatures of continental crust (Kelemen, 1995; Plank, 2005; Lee et al., 2007). Of interest here is how magmatism influences crustal thickness. A thickened/thinned arc crust will have a strong influence on the depth of mantle melting and intracrustal magmatic differentiation as well as development of crustal thermal structure, which suggests there may be dynamic feedbacks between magmatic flux and crustal thickness (Hildreth and Moorbath, 1988; Lee et al., 2007; Chiaradia, 2015; Turner et al., 2016). With thick crust, continental arcs often become high-standing features on Earth and thus may also impact atmospheric circulation and climate (Molnar and England, 1990; Lee et al., 2015).

What controls crustal thickness is the interplay between tectonic forces, magmatic addition and erosion (Karlstrom et al., 2014; Lee et al., 2015; Cao and Paterson, 2016). Both tectonic shortening and influx of mantle-derived magma are processes that thicken the crust, triggering large scale uplift and corresponding erosional processes that thin the crust. Previous studies emphasized the role

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of tectonic shortening in crustal thickening (Allmendinger et al., 1997; Haschke and Günther, 2003; Cao and Paterson, 2016). However, continental arcs are characterized by voluminous magmatic flare-ups over tens of millions of years (Ducea, 2001; DeCelles et al., 2009), during which magmatic thickening may be significant. Observations in modern continental arc volcanoes suggest that considerable surface uplift accompanies magmatic input (Fialko and Paearse, 2012; Ward et al., 2014), indicating a large contribution of magmatism to crustal thickening. Close temporal links between high magmatic influx and rapid arc unroofing in ancient arc systems also suggests an important role of magmatism in modulating topography, which in turn controls erosion (Kimbrough et al., 2001). How this dynamic link between magma addition and surface response influences crustal growth in continental arcs is not well understood, mainly because the magnitudes and timing of magmatic and erosional fluxes are not well constrained.

Here, in a case study of forearc sediments derived from a segment of the Cretaceous North American Cordilleran arc, we estimate magmatic addition and erosion rates from established geochronologic data in the arc batholith, along with our own geochronologic and barometric constraints from detrital minerals in forearc sediments. We show from mass balance and isostatic modeling that magmatic thickening was significant during a magmatic flare-up in this arc, and that erosion responded quickly, lagging behind peak magmatism by 3–6 Myr. We propose that this dynamic link between magmatism and erosion dictates the evolution of crustal thickness as well as crustal thermal structure in continental arcs.

2. Peninsular Ranges Batholith and forearc basin

The northern Peninsular Ranges Batholith (PRB) in southern California is one segment of the Cordilleran arc that developed on the western margin of North American continental crust during eastward subduction of the Farallon oceanic plate. The batholith consists of gabbroic to granitic plutons intruded into Paleozoic–Jurassic meta-sedimentary rocks. Emplacement of PRB plutons began in Middle Jurassic time, but most of the batholith was emplaced between 125 and 80 Ma, among which the 100–90 Ma La Posta-type plutons comprise more than 40% of the northern PRB (Kistler et al., 2003; Shaw et al., 2003; Morton et al., 2014; Premo et al., 2014) (Fig. 1). The batholith has been divided into western, eastern, and upper plate zones that are distinct in composition and age (Gastil, 1975; Todd et al., 1988; Kistler et al., 2003; Lee et al., 2007; Morton et al., 2014). The older western zone plutons (125–105 Ma) are gabbroic to tonalitic in composition, and intruded into a prebatholithic basement consisting of Mesozoic island arcs accreted to North America during Late Jurassic–Early Cretaceous extensional subduction (Lee et al., 2007; Morton et al., 2014). Younger eastern zone plutons (105–90 Ma) are predominately granodioritic in composition, and were emplaced through the Paleozoic North American continental margin during a compressional subduction phase (Lee et al., 2007; Morton et al., 2014). The upper plate zone comprises granitic plutons of 92–80 Ma age emplaced into an allochthonous crustal block (Todd et al., 1988; Morton et al., 2014). Eastward younging of the plutons may have been caused by arc front migration due to slab flattening (Grove et al., 2003; Morton et al., 2014) or reduction of the mantle wedge by crustal thickening (Karlstrom et al., 2014). These three zones are separated by two narrow synbatholithic ductile shear zones developed ∼118–105 Ma and ∼90–80 Ma, respectively (Todd et al., 1988; Morton et al., 2014). Regional scale contraction mostly occurred in the backarc and was complete by 105 Ma (Kimbrough et al., 2001; Grove et al., 2008). Apart from two shear zones, the PRB plutons are undeformed to weakly deformed, indicating that the stress regime in the shallow crust within the arc was neutral to extensional during pluton emplacement (Kimbrough et al., 2001).

Throughout the batholith, Al-in-hornblende thermobarometry of exposed plutons as well as contact metamorphic phase equilibria suggest plutons were emplaced at depths of 10–20 km, with shallower depths recorded in the western part of the batholith (Ague and Brandon, 1992; Todd et al., 2003). The west–east increase in emplacement depths is considered to be a result of Neogene regional uplift associated with rifting of the Gulf of California (Silver and Chappell, 1988; Todd et al., 2003). Thermochronologic studies of the plutons by Grove et al. (2003) and Miggins et al. (2014) suggest progressive cooling from west to east following magmatic emplacement, which they attribute to denudation related to magmatic thickening and/or refrigeration by slab flattening.

Sedimentation in the PRB forearc started as early as early Aptian (122–115 Ma) (Grove et al., 2008). Rapid sedimentation during Cenomanian–Turonian time (100–90 Ma) coincided with emplacement of the La Posta-type plutons. Sequences of forearc strata (2–12 km) developed from the Cenomanian to Eocene in coastal plain and offshore environments along the western flank of the Peninsular Ranges, extending from the northern Santa Ana Mountains to Baja California (Fig. 1) (a summary of the Upper Cretaceous–Lower Eocene PRB forearc strata is included in supplementary material S1). Petrographic studies suggest that the pre-Cenomanian forearc sediments consist mainly of metamorphic and volcanic detritus, representing erosion of old wall rocks and unroofing of the volcanic cover of the arc (Grove et al., 2008). A shift in provenance rock types occurred after the late Cenomanian–Turonian, when detritus from plutonic materials with detrital zircon ages similar to those in the PRB became dominant in the forearc sediments, indicating that by ∼90 Ma, the PRB had become a continuous, high-standing topographic feature that isolated the forearc basin from inboard source regions (Nordstrom, 1970; Schoellhamer et al., 1981; Girty, 1987; Sharman et al., 2014). Ages of detrital zircons from forearc sediments deposited during Late Cretaceous–Early Paleogene time suggest that these sediments were derived exclusively from the PRB (Sharman et al., 2014). Unroofing of most of the PRB was largely complete by the end of the Cretaceous. Paleogene stability of the PRB is indicated by >50 Ma apatite fission track ages, preservation of Paleocene–Eocene paleosols, development of Eocene erosional surfaces, and transition from local PRB to extraregional sediment provenance after late Paleocene (Santa Ana Mountains area) – early Eocene time (San Diego area) (Minch, 1979; Abbott, 1981; Miggins et al., 2014; Sharman et al., 2014).

Kimbrough et al. (2001) and Grove et al. (2003) proposed that the close temporal relation between the voluminous magma emplacement of the La Posta suite and the rapid sedimentation initiated in Cenomanian–Turonian indicates strong coupling between high flux magmatic addition and arc exhumation. Lack of large scale contraction throughout the batholith during the magmatic flare-up suggests that the PRB likely represents an example of an arc in which the erosional topography and crustal growth were primarily driven by magmatic thickening (Kimbrough et al., 2001). Understanding how erosion responded to magmatism and the extent to which magmatism and erosion influenced crustal thickness evolution requires quantitative constraints on rates of magmatism and erosion through time.

3. Approaches

3.1. Magmatic addition rates

Magmatic addition rates can be estimated from age distributions and areas of different intrusive suites of the PRB. We com-

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