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Coupled feedbacks between mountain erosion rate, elevation, crustal temperature, and density

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ABSTRACT

Many ancient (>1 Gyr) mountain belts have crust >50 km thick, in contrast with isostatic and erosion models that predict crustal attenuation to ∼30 km in <100 My. One proposed explanation is that thick crustal roots are preserved through a feedback in which the gradually cooling crust grows progressively denser, floats lower in the mantle, and erodes more slowly, thereby slowing crustal destruction. To explore this feedback, we develop a 1-D numerical model for the thermal and density evolution of an orogen after tectonic growth has stopped. Our simulations show that this densification feedback can indeed slow crustal destruction and help preserve thick crust. These simulations also show that crustal preservation is promoted by erosion rates that result in pressure–temperature conditions favorable for garnet-forming metamorphic reactions, which sharply increase lower crustal density and amplify the densification feedback. We find that the strength of the densification feedback depends nonlinearly on the ratio between advective and conductive cooling, such that crustal preservation is maximized at intermediate values of this ratio. This model predicts secular trends in elevation, erosion rate, and crustal thickness consistent with measured values in orogens up to several hundred My, but not in older orogens, suggesting that processes beyond those in the model (e.g., sedimentation, increasing plate strength, dynamic topography, chemical weathering) may be necessary to generate positive elevations and erosion rates in ancient orogens. This analysis suggests that the feedback between erosion, crustal cooling, and elevation can significantly affect the evolution and longevity of the continental crust.

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1. Introduction

The elevation of Earth's surface, from the summits of the tallest mountains to the depths of the ocean's abyssal plains, is dominantly controlled by isostasy, the principle that the crust floats on the mantle at a height determined by the crustal thickness and the density difference between the crust and denser mantle. The collision of continental crust at plate boundaries can thicken the crust up to 70 km, leading to isostatically compensated mountains that reach thousands of meters above sea level. Just as isostasy leads to the birth of mountains, it also controls the response of mountain belts to erosion: as rocks are eroded from the surface and transported away, the crust buoyantly rebounds.

The isostatic response to erosion has important consequences for the evolution of Earth's crust over geologic time. As erosion thins the crust, isostatic uplift slows the rate at which crustal elevation declines toward sea level. This ensures that the crust is exposed to erosion for a longer period of time – and therefore grows thinner – than it would in the absence of isostasy. This isostatically modulated erosion is thought to be capable of rapidly thinning the crust. Indeed, the combination of isostasy and erosion has been conjectured to be so efficient at destroying crust that a mountain belt in isostatic equilibrium should thin to <30 km, and that elevations and erosion rates should drop to nearly zero, in less than 100 million years (My) (Pazzaglia and Brandon, 1996; Pinet and Souriau, 1988). This simple model, however, is inconsistent with the observation that the continental crust is, on average, ∼40 km thick, and that many ancient mountain belts maintain thick crustal roots (>50 km) hundreds of millions of years after the cessation of crustal thickening. This raises the question: what does this simple isostatic model not capture?

Several mechanisms have been proposed to explain the rate of post-orogenic decay and the preservation of thick crustal roots over billions of years. Some studies have explored geomorphic explanations for the deceleration of erosion rate. Pinet and Souriau (1988), for instance, described erosion rates with two linear func-

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tions of elevation, fitting one trend to regions older than 250 Ma and a steeper trend to regions younger than 250 Ma, arguing that the differences reflect changes in the magnitude and geographic locus of continental sedimentation and erosion with time. Other studies investigating the erosion mechanisms governing post-orogenic decay have pointed to the changing role of sediment supply in fluvial erosion of bedrock (Egholm et al., 2013; Sklar and Dietrich, 2001). Baldwin et al. (2003), for example, propose that erosion rates would decline as fluvial erosion transitioned from detachment-limited to transport-limited during orogenic decay.

Other studies have explored the influence of processes inside the lithosphere, rather than on its surface. Fischer (2002) explored the influence of crustal density changes on mountain belt evolution as an explanation for seismic observations of deep roots beneath ancient mountains. In a global survey of mountain belts, Fischer (2002) observed that the ratio (R) of mountain belt surface relief to root thickness decreases with mountain belt age. To explain the sharp decrease in R early in a mountain belt's evolution (<300 Ma) and the coincident increase in crustal root density, Fischer suggested that lithospheric cooling and metamorphic phase changes could make the lower crust denser. This densification would reduce the buoyancy of the lithosphere, diminishing the uplift that occurred in response to subsequent erosion, which would reduce elevation and preserve deep crustal roots. Recently, Lee et al. (2017) explored the influence of crustal densification on crustal elevation and thickness, suggesting that crustal cooling and the growth of cold, dense mantle roots increase mean lithospheric density, which in turn decreases crustal elevation, eventually leading to increases in crustal thickness through marine sedimentation.

Support for the densification hypothesis is provided by petrologic observations and models that show that the density of lower crustal igneous rocks can be strongly affected by temperature-dependent phase changes in the lower crust. Observations from lower crustal terranes show that igneous textured lower crust granulites can be emplaced at temperatures as high as 1000 °C and pressures of 1.0 GPa (Williams et al., 2000). The base of the crust will cool gradually by conduction and erosionally-driven advection toward the surface. Xenolith P–T studies and thermochronology on lower crustal xenoliths show that these formerly hot, deep rocks cool to temperatures <600 °C (Blackburn et al., 2011, 2012), consistent with the geothermal gradients that characterize stable regions (Furlong and Chapman, 2013). These temperatures (600–1000 °C) and pressures (1–1.5 GPa) are significant for crustal evolution because they are the conditions predicted to result in the growth of garnet-bearing phases for the mafic compositions found in the lower crust (Williams et al., 2014).

The growth of garnet-bearing phases is a particularly effective driver of crustal densification. Both laboratory measurements of garnet-producing reactions (Green and Ringwood, 1967; Fig. 1) and predicted equilibrium phase assemblages in the lower crust (e.g., Connolly and Petrini, 2002) suggest that the bulk density of the lower crust should increase by as much as 10% as a result of cooling from 1100 to 600 °C (Jull and Kelemen, 2001; Williams et al., 2014). Observations for this kind of "retrograde" garnet growth have been documented in mafic granulites from the Tasiusarsuag terrane, West Greenland (Dziggel et al., 2012) and in mafic and intermediate composition intrusives in the Athabasca terrane, Canada (Williams et al., 2014). These observations suggest that metamorphic phase changes in the lower crust – particularly those that produce garnet – may be an important component of the proposed densification feedback, and hence may significantly influence crustal isostasy and surface elevation.

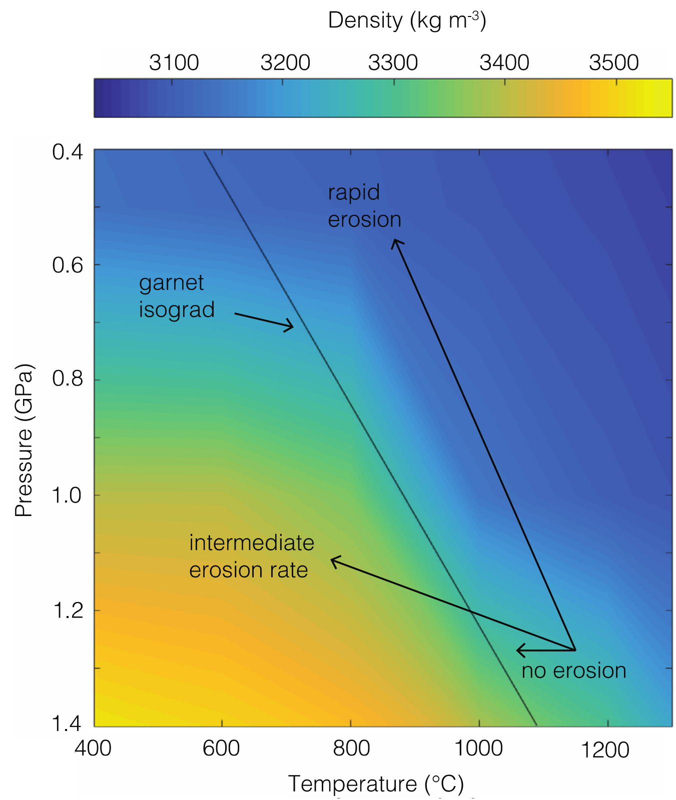

Fig. 1. Conceptual illustration of the effects of erosion rate on lower crustal densification. Colors show lower crustal density predicted for a mafic composition as a function of pressure and temperature (Jull and Kelemen, 2001). Garnet-forming metamorphic reactions, which increase rock density, are favored to the left of the garnet isograd (Green and Ringwood, 1967). Arrows show hypothetical pressure–temperature trajectories for parcels of rock initially at the base of three lithospheric columns, one subjected to rapid surface erosion, another to intermediate erosion rates, and one to no erosion. In this illustration, only under intermediate erosion rates does the lower crust sharply increase in density, suggesting that the densification feedback could be strongest at intermediate erosion rates. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

For this to be the case, however, igneous rocks in the lower crust must pass through pressure (P) and temperature (T) conditions that permit garnet growth (Fig. 1). Whether or not lower crustal rocks cross this threshold depends on the region's erosional history. In a region with no erosion, lower crustal pressures would remain steady and temperatures would drop so slowly that garnet growth would be inhibited by the long timescales required to reach the necessary P–T conditions. Under these conditions, lower crustal density would remain nearly steady (Fig. 1), implying that the densification feedback should be weak at very low erosion rates. Likewise, in a region undergoing exceptionally fast erosion, pressures would drop rapidly, but temperatures would not drop fast enough for garnet to form. In this case, lower crustal density would not increase and may even decrease, implying that the densification feedback should be weak at very high erosion rates. In a region with intermediate erosion rates, however, temperatures may drop rapidly enough for the lower crust to migrate into P–T conditions favorable for garnet growth. In this case, lower crustal density would increase sharply due to metamorphic phase changes. These examples suggest that the densification feedback could be nonlinearly dependent on surface erosion, with a strong feedback at intermediate erosion rates and a weaker feedback at both low and high erosion rates.

The dependence of densification on erosion is complicated by the possibility that erosion rates themselves may be affected by densification. Given the tendency of erosion rates to

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