flow pattern does not seem to be strongly dependent on the seismic model or density scaling[9], suggesting that the tomographic inversions can be used to identify regions of sheared flow with reasonable confidence.

There are some regions of intraplate volcanism in Africa and Asia where the correlation fails. The volcanism in both regions has been previously explained by a mechanism termed edge-driven convection[10,11], where a horizontal temperature gradient resulting from a vertical material boundary such as a continental root drives small-scale convection. It is encouraging that there are alternative explanations for these two volcanic areas with low shear. Some recent volcanism in eastern Europe also occurs over a low-shear region. However, there may not be a specific explanation for each area where the correlation fails: shearing by itself is not sufficient to generate melt, it must be accompanied by variations in material strength or composition, or by some other physical process. All in all, the reported correlation between regions of inferred strong shear and intraplate volcanism is quite impressive.

As Conrad and colleagues discuss, shearing of the global flow beneath plates could result in magma melt through other physical mechanisms than the shear-induced upwelling that they favour. These include fracturing of the lithosphere where the mantle flow shears against its base or weakening of the lithosphere by shear-induced strain. Alternatively, more traditionally considered processes such as active upwelling of mantle material, for example in plumes or small-scale convection cells, can also result in large shear and hence melting.

Whether intraplate volcanism is the result of one of the processes discussed above or another, as yet unidentified mechanism, the findings presented by Conrad and colleagues[4] suggest that melting is nearly ubiquitous in the uppermost mantle. The small change in pressure experienced by a parcel of mantle displaced vertically only slightly by the shear instability mechanism can produce melt only if the shallow upper mantle is nearly at the solidus temperature everywhere. If this were not the case, the locations of melting would more than likely be correlated with warmer regions of the upper mantle rather than shear.

Conrad and colleagues[4] identify a correlation between volcanism and shear between the plate and mantle that provides an important step in understanding volcanism on Earth. ❐

Scott D. King is in the Department of Geosciences, 4044 Derring Hall (0420), Virginia Tech, Blacksburg, Virginia 24061, USA.
e-mail: sdk@vt.edu

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GEODYNAMICS

Mantle-controlled mountains

Mountain-forming systems on Earth occur at present either at the edge of continental plates or in their centre. Isotopic signatures from orogenic rocks worldwide indicate that these two distinct systems have existed for at least 550 million years.

Heinrich Bahlburg

Most of the prominent mountain chains on Earth fall into one of two classes. External mountain belts are located at the margins of continents: the ocean floor sinks into the mantle below the continent and causes uplift at the boundary. Internal mountain belts, by contrast, are now present within continental interiors where two continental plates have collided. These two distinct classes of mountain-forming, or orogenic, systems seem to have been significant features of Earth's crustal evolution for at least the past 550 million years (Myr)[1,2]. Writing in *Nature Geoscience*, Collins *et al.*[3] report that internal and external mountain chains each have a distinct and persistent hafnium isotope signature that allows reconstruction of the provenance of the subducted material over time, and may bear witness to the long-lived mantle convection that drives plate movement.

Both internal and external mountain chains ultimately result from the subduction of oceanic lithosphere. Because the lithosphere — the outer rigid shell of the Earth — is denser beneath the oceans, oceanic lithosphere tends to subduct under the more buoyant continents at convergent plate margins. In this process, some material is scraped off the down-going plate and accreted to the overriding continental plate. The overriding continental crust becomes marked with the geochemical signature of the oceanic lithosphere, which can be identified by its enrichment in the radiogenic isotopes of hafnium[4]. By contrast, the continental lithosphere has a lesser-to-unradiogenic hafnium isotope signature.

The external mountain belts found at present on Earth are located along the Pacific Ocean margins, predominantly oriented in a north–south direction (Fig. 1a). Spanning the margins of the Americas, Asia and Australasia, these external orogens are generated and persist through the continuous subduction of dense Pacific Ocean lithosphere that is constantly created at a far-off mid-ocean ridge; as a consequence of mid-ocean spreading, this new material moves away from the ridge, increases in density through cooling and can finally be subducted beneath a convergent plate margin.

At mountain belts in the interior of continents by contrast, the down-going plate is characterized by a string of fragments of oceanic and continental lithosphere. Initially, a section of dense

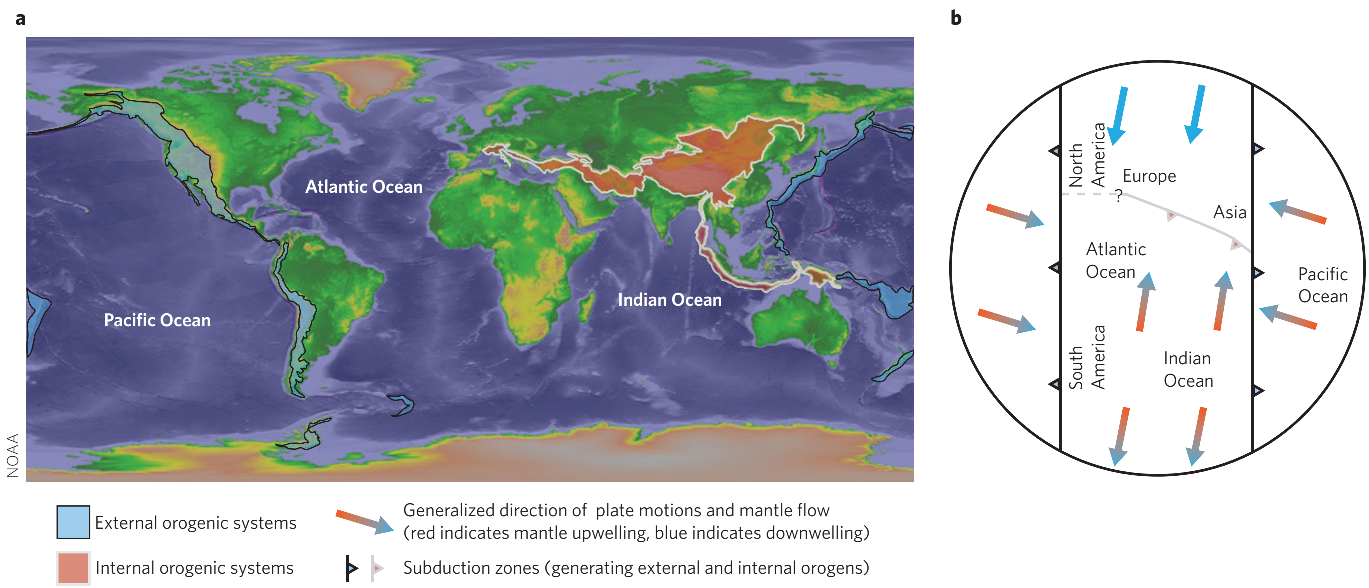

Figure 1 | The present-day distribution of external and internal mountain belts. **a**, Collins and colleagues[3] show that external mountain belts, formed at convergent continental margins, and internal mountain belts, formed in continental interiors, each have a distinctive trend in their hafnium isotope signature that has persisted for 550 Myr. The isotopic signatures reflect the different subduction histories of the mountain-forming systems, and their longevity implies that persistent convection in the underlying mantle may provide a fundamental control on orogenic evolution. **b**, A conceptual model of two principle convection cells that may govern the evolution of internal and external mountain belts, abstracted from ref. 7. Labels indicate in a very schematic way the location of the main continents and oceans.

ocean lithosphere falls away beneath the buoyant continent. Once this section is completely consumed through continued subduction, the ocean basin closes and the original continent of the overriding plate collides with the continental fragment that borders the consumed oceanic plate. This happened, for example, when Africa began to collide with Europe, when India collided with Asia and, at present, as Australia is colliding with Asia. Most of these continental collisions took or take place along a system of east–west oriented subduction zones. When two pieces of continental lithosphere have collided, the continuing movement of the plates towards each other can initiate the subduction of the next ocean basin outboard of the originally subducting plate. Essentially, the subduction zone steps backwards and a second cycle of ocean basin closure[5] is initiated. Over time, many initially separate continental fragments can be assembled into one continent, as the intermittent pieces of oceanic lithosphere consecutively sink into the mantle.

Collins and colleagues[3] aim to reconstruct the subduction characteristics in both external and internal regimes by compiling the hafnium isotope signatures of the mineral zircon in rocks taken from mountain belts globally. They measured the age of the zircons using uranium–lead dating, and found that the hafnium isotopic signature of those collected in external orogens has continuously evolved towards more radiogenic hafnium compositions since 550 Myr ago. The isotopic signature of mountain belts within continents, on the other hand, is mostly mixed and covers a wide range between radiogenic and unradiogenic compositions.

Because the radiogenic component is thought to come from the juvenile oceanic lithosphere, Collins and colleagues suggest that the increasingly radiogenic signature for the mountain belts at the edge of continents reflects the persistent subduction of oceanic material. The trend is not perfectly linear and does include many deviations over timescales of less than 50 Myr[6]. So the process is probably only quasicontinuous. The mixed radiogenic and unradiogenic signal observed at mountains in the interior of continents, in turn, is thought to reflect the episodic mixing between young oceanic and evolved continental lithospheres over a number of cycles of ocean basin closure.

The persistence of the trend in the hafnium isotope signatures over time indicates that the two types of orogenic system have existed on Earth for at least the past 550 Myr. By implication, equally persistent fundamental principles must govern the evolution of mountain ranges on Earth. Collins and colleagues[3] argue that two large-scale convection cells exist in the Earth's mantle[7]. They suggest that one convection cell is located beneath the present-day positions of Africa and Asia, and the other beneath the Pacific Ocean (Fig. 1b).

In a generalized way, mantle flow beneath Africa and Asia is dominantly towards the northeast and southwest. The internal subduction systems are located in this convection cell and flow in the mantle below may govern the evolution of these mountain belts[7]. The Pacific Ocean cell is characterized by ascending mantle flow underneath the Pacific mid-ocean ridges and dominantly northwest–southeast orientated convection away from the ridges. Collins and colleagues[3] suggest that the circum-Pacific external subduction system forms the downwelling boundary between the two cells and argue that this boundary has been stable for at least 500 Myr. This idea contrasts with numerical models of mantle convection[8]. These models imply that Earth's convection varies over time and exhibits short-term variability. And such variability should prevent formation of large-scale convective cells that are stable for hundreds of millions of years.

It remains unknown why two contrasting orogenic systems formed around 550 Myr ago because little is known about the existence, or not, of similar long-lived systems before this time. It is similarly unknown what caused the inception of the two systems at that point in time.

Collins and colleagues[3] provide a systematic consideration of the Phanerozoic evolution of mountain belts and confirm that two types of mountain-forming system have existed on Earth since 550 Myr ago. The study provides a testable model for mantle control on orogenic evolution, and hence an excellent starting point for further exploration that will enable us to refine our understanding of mantle convection, and the link between convection systems and the geochemical and structural evolution of the orogenic crust. ❐

Heinrich Bahlburg is at the Institut für Geologie und Paläontologie, Westfälische Wilhelms-Universität, 48149 Münster, Germany.
e-mail: HBahlburg@uni-muenster.de

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CARBON CYCLE

Storage beneath mangroves

Empirical data on mangrove carbon pools and fluxes are scarce. A field survey in the Indo-Pacific region suggests that the sediments below these remarkable trees hold exceptionally high quantities of carbon.

Steven Bouillon

Mangrove forests are diverse, highly productive ecosystems that stretch along the intertidal zone of tropical and subtropical coastlines. These forests provide a wealth of ecosystem services. They are often associated with highly productive fisheries — although the causal mechanisms are a matter of debate — and are thought to export to the coastal zone a significant amount of the carbon they fix, either as organic or inorganic carbon. Despite their impact on carbon cycling and ecology, however, large uncertainties exist regarding the productivity and areal extent of mangrove forests, and the amount of carbon stored in their sediments[1]. Writing in *Nature Geoscience*, Donato and colleagues report that mangrove forests surrounding the Indian and Pacific oceans are among the most carbon-rich forests in the tropics[2].

Mangrove forests consist of a consortium of tree and shrub species adapted to cope with the saline conditions and fluctuating water levels that characterize their environment. One such adaptation is the development of different aerial root systems, such as stilt or prop roots (Fig. 1), that anchor the plants in the sediment and allow oxygen to penetrate the submerged roots. These complex root structures also slow down incoming waters during tidal inundation, causing much of the suspended material in the water column to settle onto the sediment surface. This highly efficient particle-trapping mechanism[3] leads to the sequestration of carbon not only from the mangroves — for example, from leaf and root litter — but also from outside the ecosystem, including from rivers and adjacent seagrass meadows. These coastal carbon sinks are thought to bury carbon at rates up to 50 times higher than those in tropical rainforests[4], where local vegetation is the predominant carbon source.

Figure 1 | Mangrove forest in Gazi Bay, Kenya. Mangroves trees possess highly developed and complex root structures that slow down the flow of water during tidal inundation, causing carbon-containing particles suspended in the water column to settle on the sediment. Donato and colleagues[2] measured whole-ecosystem carbon storage in 25 mangrove forests in the Indo-Pacific region. They show that mangroves are among the most carbon-rich ecosystems in the tropics, and suggest that clearance of these forests could lead to large emissions of carbon dioxide.

Mangrove forests are rapidly disappearing owing to human interference, with up to 50% being lost over the past 50 yr, primarily because of harvesting and land conversion[5]. The impact of such losses goes beyond a decrease in carbon sequestration. As forests are removed, the organic carbon built up over decades to millennia is subject to increased remineralization and erosion, and therefore to release — *in situ* or elsewhere — to the atmosphere as carbon dioxide. However, the climatic impact of mangrove loss is difficult to gauge. It is known that mangroves can develop very deep organic sediments — deposits of ten metres have been reported in the Caribbean[6]. But there are insufficient data to quantify mangrove carbon stocks on a global scale, because the combination of data required is rarely measured.

Donato and colleagues[2] help to fill the gaps by quantifying above- and below-ground carbon pools in 25 mangrove systems across the Indo-Pacific region. Above-ground pools, inferred from standing-tree and dead-wood biomass, were significant, averaging 159 Mg C ha^{-1}. But below-ground pools — assessed by measuring carbon content, density and depth in an impressive number of sediment cores — proved to be exceptionally high and the dominant