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Two contrasting Phanerozoic orogenic systems revealed by hafnium isotope data

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Two fundamentally different orogenic systems have existed on Earth throughout the Phanerozoic. Circum-Pacific accretionary orogens are the external orogenic system formed around the Pacific rim, where oceanic lithosphere semicontinuously subducts beneath continental lithosphere. In contrast, the internal orogenic system is found in Europe and Asia as the collage of collisional mountain belts, formed during the collision between continental crustal fragments. External orogenic systems form at the boundary of large underlying mantle convection cells, whereas internal orogens form within one supercell. Here we present a compilation of hafnium isotope data from zircon minerals collected from orogens worldwide. We find that the range of hafnium isotope signatures for the external orogenic system narrows and trends towards more radiogenic compositions since 550 Myr ago. By contrast, the range of signatures from the internal orogenic system broadens since 550 Myr ago. We suggest that for the external system, the lower crust and lithospheric mantle beneath the overriding continent is removed during subduction and replaced by newly formed crust, which generates the radiogenic hafnium signature when remelted. For the internal orogenic system, the lower crust and lithospheric mantle is instead eventually replaced by more continental lithosphere from a collided continental fragment. Our suggested model provides a simple basis for unravelling the global geodynamic evolution of the ancient Earth.

Present-day orogens of contrasting character can be reduced to two types on Earth, dominantly accretionary or dominantly collisional, because only the latter are associated with Wilson cycle tectonics (for example, refs 1–3). The hemispheric circum-Pacific system is characterized by ongoing subduction and accretion of oceanic material[4–8] and forms a semicontinuous, broadly meridional system of accretionary orogens around the Pacific margin, the locus of which is outlined by the Pacific 'Ring of Fire'. Opposed subduction zones exist on either side of the Pacific Ocean, driven by subducted oceanic lithosphere that originates at the East Pacific Rise (EPR). The circum-Pacific orogens have existed around the margin of Pangea at least since the Mesozoic (Fig. 1) and have been called peripheral orogens[9]. By contrast, the Alpine–Himalayan–Indonesian subduction system is broadly latitudinal, extending semicontinuously from the Indonesian arc and Papuan fold belt in SE Asia to the Betics of the western Mediterranean. It is associated with northward transport of Gondwanan landmasses, including Africa, India and Australia, into a collisional zone associated with irregular but persistent N-dipping subduction (for example, ref. 10). Subduction systems like the Alpine–Himalayan–Indonesian chain ultimately produce collisional orogens such as the European Alps, Urals and Himalayas, and is characterized by a form of Wilson cycle tectonics. Because these orogens ultimately become incorporated into the continental interior, they have been referred to as interior orogens[9]. The interior versus peripheral distinction highlights the distribution of these orogens relative to supercontinents, reflecting their different geodynamics and consequent isotopic evolution.

Orogenic systems and mantle convection cells

The contrasting orogens have existed throughout the Phanerozoic era[1,2,11]. During the Paleozoic, the circum-Pacific orogens were represented by Terra Australis[11], the North American Cordillera, which probably began by the Early Ordovician[12], and the Early Paleozoic accretionary orogens in the easternmost Altaids of Asia[13]. Beginning with the Permo-Triassic Gondwanide Orogen[14], the Mesozoic circum-Pacific orogens were also represented by the North American Cordillera and its western extension into Siberia and eastern China/Japan. On the other hand, the Alpine–Himalayan–Indonesian collisional orogens can be traced throughout Asia and Europe. The Eurasian orogens are a complex collage of juvenile oceanic material and variably-sized continental fragments that include the Central China orogen (Dabie Shan), the Altaids, Uralides, Variscides and Caledonides, as well as the present-day Alpine–Himalayan orogenic system. The Eurasian orogens formed and are forming by accretion of Gondwanan blocks to landmasses farther north. Most fragments were successively isolated from the Gondwanan landmass as the Tethyan then Indian mid-ocean ridge systems jumped southward, partly in response to successive accretion of the continental fragments into Asia[1,2,10].

Successive collisional orogens in Eurasia are progressively younger eastward in the Paleozoic, then southward in the Mesozoic (Fig. 1). For example, following the collision of Baltica with Laurentia in the Late Silurian[15] forming the Caledonides, Siberia collided with Baltica, forming the Uralides in the Late Carboniferous[16]. Farther east, the North China block collided with the southern margin of Siberia in the Permian[13] forming the Altaids, then the South China block with the southern margin of North China in the Triassic, producing the Qinling–Dabie orogen[17]. The Lhasa terrane accreted into Asia from the south in the Early Cretaceous[18] and India collided with Asia in the Paleocene[19] forming the Himalayan orogen. Australia began colliding with southeast Asia in the Neogene[20] and is still moving northward.

We consider these fundamentally different types of orogens reflect the arrangement of two, global-scale mantle convection

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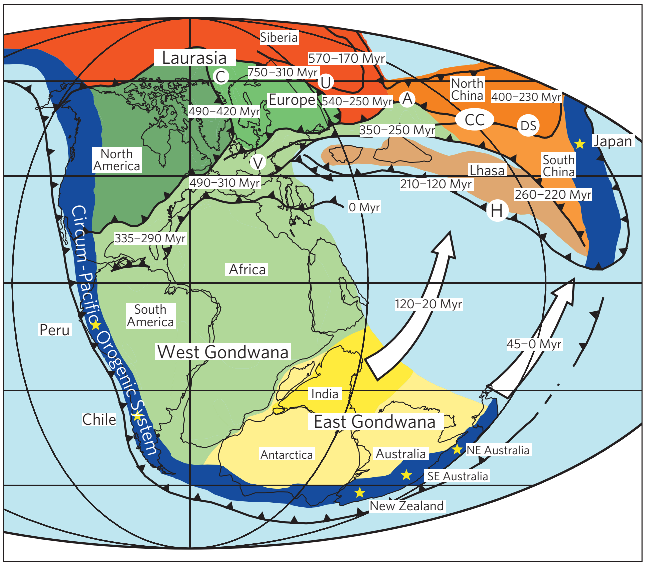

Figure 1 | Location of Phanerozoic internal versus external orogenic systems, based on a Jurassic reconstruction[39]. The external (circum-Pacific) system comprises a number of discrete orogens that, together, have probably existed for 550 Myr. The internal system has existed for a similar period, but each orogen is separated by a cratonic block or continental ribbon. Each internal orogen has much shorter duration (generally <200 Myr) and the terminal orogenic phases of each Asian orogen are progressively younger southward, reflecting successive accretion of continental fragments from the south. A=Altaids; C=Caledonides; CC=Central China orogen; DS=Dabie Shan; H=Himalayas; U=Uralides; V=Variscides. Stars are sample locations for external orogenic system. Red = Siberia/Arctida; dark green = Laurentia/Baltica; light green = West Gondwanan fragments; yellow = East Gondwanan fragments; orange = Chinese cratons and Cimmerian terraces; Blue = circum-Pacific orogenic system.

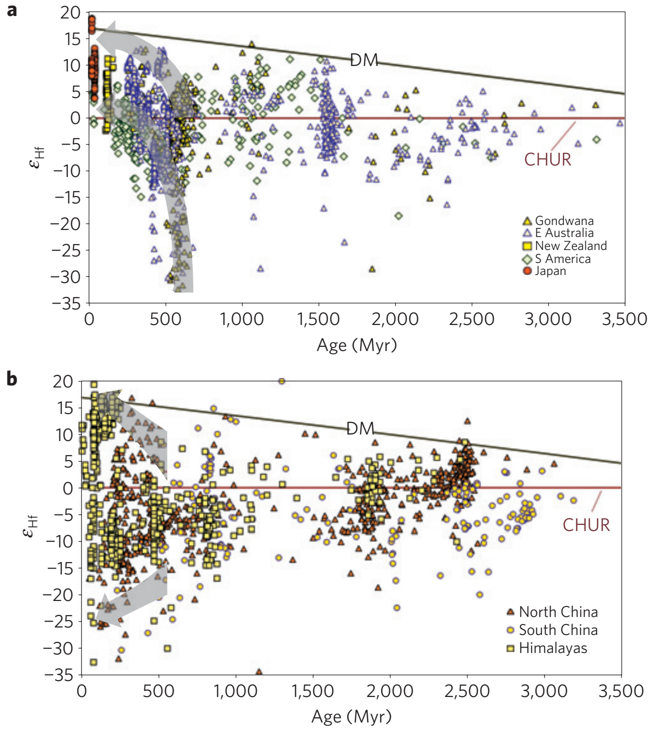

Figure 2 | Contrasting hafnium isotopic signature for Phanerozoic orogenic systems: external (a) and internal (b). Note the fanning isotopic array of **b** from ~550 Myr, in contrast to the contracting array of **a**. Note also that in **a** the progression towards increasingly juvenile Hf isotope compositions after 550 Myr is shown by individual segments of the orogenic system, such as the Tasmanides of eastern Australia, and is also evident in Nd isotopes[26]. Explanation in text. DM represents a generalized 'Depleted Mantle' growth curve, whereas CHUR denotes the chondritic reference. Colours in **b** match those of Fig. 1.

cells that have persisted throughout the Phanerozoic[2]. The circum-Pacific orogens can be geodynamically grouped as those forming at the stable boundary between the two cells. For this reason, they are called the external orogenic system. On the other hand, the Alpine–Himalayan and other interior orogens of Pangea were short-lived, and have successively stepped clockwise within the internal part of one (Pangean) convection cell[2] (Fig. 1). These are grouped as the internal orogenic system. These terms highlight the relation of orogenic systems to mantle convection cells rather than to the supercontinental cycle.

Relation of hafnium isotopes to orogenic systems

The evolution of these contrasting orogenic systems can be explored by Hf isotope variations in detrital and igneous rock-hosted zircons. Hf isotopic systematics can distinguish between orogenic processes dominated by the generation and reworking of continental crust and those dominated by additions of juvenile crust. Figure 2 reveals clear differences in the Hf isotope record of the internal (for example, Alpine–Himalayan–Indonesian) and external (circum-Pacific) orogens that reflect fundamental differences in their long-term evolution.

The most critical difference between the two orogenic systems relates to the period from ~550 Myr to the present (Fig. 2a). During this period, zircons sampling the circum-Pacific system define a broad data band that contracts and shifts towards progressively more radiogenic Hf isotope compositions, where the lowest ε_{Hf} values increase from −32 at ~550 Myr to −1 at 25 Myr and the highest ε_{Hf} values increase from +5 to values approaching those of the contemporary depleted mantle (~+18) over the same time interval. By contrast, the band of Hf isotope data from the internal orogenic systems produces a fanning isotopic array; from ~550 Myr to present-day (Fig. 2b) the lowest ε_{Hf} values become more negative (to −33) and the highest ε_{Hf} values become more positive (to ~+20).

Subduction symmetry control

The contrasting ε_{Hf} arrays can be explained by the differing symmetries of the two orogenic systems (Fig. 3). Subduction progressively removes ancient lower crust and subcontinental lithospheric mantle (SCLM). Removal in the external circum-Pacific system is usually permanent, because only oceanic crust forms on the subducting plate, a result of symmetrically opposed subduction systems either side of the East Pacific Rise. By contrast, the internal orogenic system is associated with asymmetric, long-term, N-dipping subduction (for example, refs 2,10,21,22) whereby fragments of Gondwanan lower crust and SCLM were attached to the subducting plate and eventually drifted northward to become involved in collisional orogenesis.

Subduction processes thermally and/or mechanically erode the lower crust and SCLM in the arc and backarc region of suprasubduction zones[23,24]. Hyndman *et al.*[23] showed that high heat flow values (70–80 mW m^{-2}) exist in many backarc (retroarc) regions around the circum-Pacific, up to 900 km inboard from the volcanic front, irrespective of whether the arcs are oceanic or continental. In the North American Cordillera, anomalously high heat flow has reduced lithospheric thickness to ~60 km beneath much of the orogen[23]. The SNORCLE refraction profiles from the Canadian Cordillera also indicate that the crust is surprisingly thin (32–36 km) for a thickened mountain belt[25], consistent with the heat flow data. The circum-Pacific backarcs are

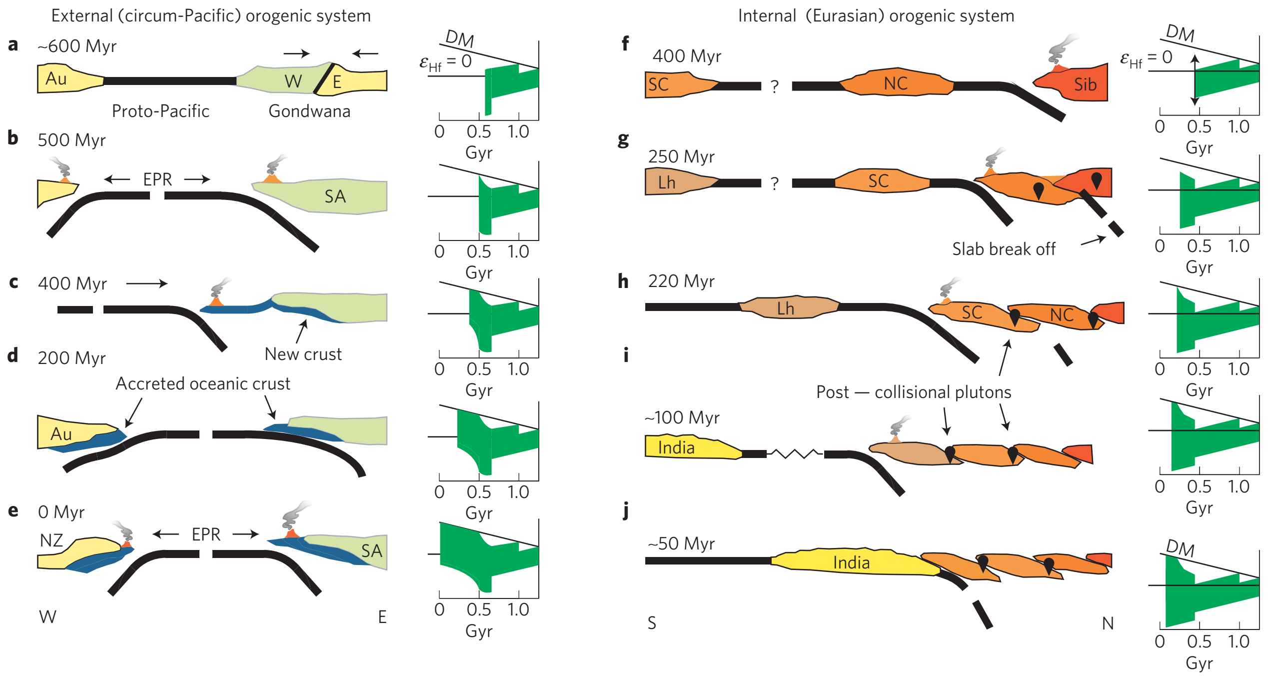

Figure 3 | Contrasting geodynamic evolution of internal and external orogenic systems. Progressive removal of old lower crust and lithospheric mantle (SCLM) from beneath the external circum-Pacific system (**a–e**) is replaced with juvenile crust, which increasingly contributes to the crustal reservoir during ongoing subduction-related magmatism. By contrast, in the internal (Eurasian) system, old lower crust and SCLM are first removed during ocean closure, but then replaced, usually by similar lower crust and SCLM (**f–j**). Subsequent 'post-collisional' plutonism reworks the replaced ancient crust and SCLM. Cartoons of Hf isotope evolution based on Fig. 2. The major rollback phase in **c** reflects general Paleozoic evolution of Tasmanides[28]. Au=Australia; EPR=East Pacific Rise; Lh = Lhasa terrane; NC=North China craton; NZ=New Zealand; SA=South America; SC=South China craton; Sib=Siberian craton.

usually hot, probably through convective thinning of lithosphere by subduction-induced mantle flow[24]. As such, maintenance of an extensive, hot backarc region is an intrinsic, long-term feature of subduction dynamics, although the efficiency of lower crust and SCLM removal is dependent on the nature of that lithosphere[24].

As lower crust and SCLM are removed, subsequent subduction-related magmatism within external orogenic systems should record a long-term shift toward increasingly positive ε_{Hf} values (Fig. 2a), reflecting continuing additions of 'juvenile' crust derived largely from the underlying convecting mantle wedge. This crust is either magmatically underplated or tectonically accreted within the arc-backarc or accretionary prism, respectively (Fig. 3b–e). The isotopic shift occurs irrespective of whether the orogen was predominantly retreating, as with the Tasmanides[26] or advancing, as with the Andes[27]. Subduction retreat and consequent outboard arc migration also ensures that the accreting juvenile material becomes isolated from the craton in retreating orogens, as with the Tasmanides during the Paleozoic[7,28]. Therefore, with successive juvenile crustal additions during ongoing arc magmatism, ancient crustal remnants and attached SCLM become a diminishing source component, as reflected in the general trend toward more radiogenic Hf isotopic compositions in zircon[26,27,29] (Fig. 3a–e). As the trend began at ~550 Myr (Fig. 2b) in the circum-Pacific system, this shows that widespread subduction began at this time, consistent with the geological evidence[11].

Subduction related magmatism in the internal orogenic system is restricted to periods of ocean closure, from subduction initiation to termination during continental collision. Figure 3f–j represents a generalized geodynamic framework showing the persistent N-directed subduction of Gondwanan fragments into Asia for over 500 Myr. Intermittent slab flipping, perhaps during closure of backarc basins or subduction of continental ribbons, may have produced localized S-dipping subduction (for example, ref. 30), but it did not change the overall northward translation of Gondwanan fragments during the Phanerozoic[2].

Arc magmatism again resulted in marked excursions of zircon Hf isotopic composition toward depleted mantle-like compositions, which produced positive ε_{Hf} values as for external orogens (for example, Fig. 3f). However, the ensuing continental collision resulted in tectonic underthrusting of a Gondwanan continental fragment and the termination of juvenile magmatic input. Any sub-arc lithosphere removed during the preceding subduction would have been replaced by crust from the Gondwanan fragment, similar to that inferred from deep seismic images of the Himalayas[31,32] and European Alps[33]. Subsequently, post-collisional magmatism associated with delamination, orogenic collapse or lithospheric extension will melt the underthrust continental fragment, thereby driving zircon ε_{Hf} to negative values that approach the Hf isotope evolution arrays of the ancient Gondwanan craton (Fig. 3g–j).

Once the continental fragment has collided and subduction ceased, the subduction zone steps to the other (southern) side of that fragment (Fig. 3g–i), and the modified Wilson cycle is repeated. Accordingly, another ε_{Hf} excursion toward DM will begin as the ocean begins to close, followed by reversion back to the dominant crustal array during terminal closure, as described above. The timing and duration of Wilson cycles will vary markedly, even along strike, because continental fragments are of irregular shape and variable size, as evident along the present-day Alpine–Himalayan orogen. Therefore, collisional events will be diachronous along the same subduction zone, and each orogen needs to be studied independently to establish the Wilson cycle duration. Nonetheless, the diachronicity of these cycles along the orogenic system generates the characteristic fanning arrays of the Hf isotope data (Figs 2a, 3g–j).

Short-term isotopic reversals

Short-term (<50 Myr) geodynamic processes that enhance melting of old crust are capable of transiently reversing the dominant, long-term, isotopic trend toward mantle-like Hf values in the external orogenic system. For example, during 'Laramide-style' orogeny, flat subduction drives the lower plate far beneath the continental interior and subsequent slab break-off or retreat causes a widespread burst of melting of the thickened crust and ancient SCLM, as with the Cenozoic Basin and Range Province of the USA (for example, refs 34,35). Similarly, the enigmatic Cretaceous 'magmatic flare-ups' of the North American Cordilleran and the Cenozoic Andes seem to be 10–20 Myr bursts of crustal melting associated with crustal thickening, when lowermost continental lithosphere was thrust beneath the arc[36,37]. In addition, crustal thickening associated with closure of oceanic backarcs has the potential to bury craton-derived turbiditic metasediments, which melt to become S-type granites during the next extensional cycle[28,38], causing pronounced but transient Hf isotopic shifts[26].

The effect of such second-order processes is to generate isotopic excursions toward negative ε_{Hf} values[26,27,29] and negative whole-rock ε_{Nd} values[36], but these are generally short-lived (<50 Myr) reversals relative to the >500 Myr, first-order process of Phanerozoic evolution outlined above, and are unlikely to obscure the main trend toward juvenile isotopic compositions in external orogenic systems. Indeed, a survey of modern continental arcs shows that most analysed rocks, ranging from basalts to rhyolites, have positive whole-rock ε_{Nd} values[36]. Accordingly, we predict that most modern circum-Pacific arc rocks will have positive ε_{Hf} values, and will cluster in the array defined on Fig. 2a.

We therefore suggest that the disparate Hf isotope evolution of the two different orogenic systems on Phanerozoic Earth (550–0 Myr) are explicable in terms of differing subduction symmetry. The symmetrical, external (circum-Pacific) system has opposed subduction zones, which results in protracted addition of juvenile crust to the orogenic segments. By contrast, the asymmetrical, internal orogenic system associated with long-term (predominantly N-directed) subduction resulted in fragmentation and collision of ancient continents or continental (mainly Gondwanan) fragments. These sequential fragmentation and collision events are recognized in the broad sense as Wilson cycles, and characterize the internal orogenic system. Also, both orogenic systems persisted throughout the assembly and breakup of Pangea, and therefore potentially provide a long-term global framework in which to understand supercontinental cycles. Thus, the recognition that these two global-scale orogenic systems can leave characteristic, long-term imprints in the zircon Hf isotope record raises the intriguing possibility that such data may offer fresh insight into determining Wilson cycle intervals, Proterozoic supercontinent cycles and the geodynamic controls on Precambrian continental growth.

Methods

Hf and U–Pb isotope (zircon) data was obtained from the described Asian and circum-Pacific various orogens (Supplementary Reference S1). Over 3,200 analyses are plotted. None were excluded. All analytical data were re-calculated using the same parameters. For the calculation of ε_{Hf} values, we have adopted the chondritic values of Bouvier *et al.*[40] ; $^{176}Lu/^{177}Hf$ (CHUR, today) = 0.0336 and $^{176}Hf/^{177}Hf$ (CHUR, today) = 0.282785 and the ^{176}Lu decay constant of $1.865 \times 10^{-11}\ yr^{-1}$ reported by Scherer *et al.*[41]. We have used Griffin *et al.*[42] values for the Depleted Mantle, where the DM has a present-day $^{176}Hf/^{177}Hf = 0.28323$, similar to that of average MORB. Assuming an initial value of $^{176}Hf/^{177}Hf = 0.27982$, this defines the DM as having $^{176}Lu/^{177}Hf = 0.0384$. For further details see the Supplementary References.

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Author contributions

E.A.B. tabulated all datasets, undertook calculations and presented Fig. 2. W.J.C. wrote the paper and drew Figs 1 and 3. All authors were involved in concept development and refinement of the final presentation.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to W.J.C.