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# Cyclicity in Cordilleran orogenic systems

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**Cordilleran orogenic systems, such as the modern Andes, are long belts of deformation and magmatism that are associated with the subduction of oceanic plates beneath continental ones. Although the oceanic plates have been thought to control the evolution of such systems, a number of processes operating in the upper continental plates have not been fully accounted for. The western American Cordilleras, for example, display a 25–50 million year (Myr) cycle of linked upper-plate processes. In a typical cycle, as the two plates converge and a magmatic arc forms, most of the continental crust shortens by thrusting behind the arc, whereas the lowermost continental lithosphere is shoved beneath the arc — a process that fuels episodic high-flux magmatism in the arc and simultaneously generates dense melt residues. On reaching a critical mass, these residues sink into the mantle, creating space beneath the arc and setting the stage for renewal of the cycle. This alternative model explains key features of Cordilleran systems, such as cyclical trends in the flux and composition of magma supplied to the upper plate, and the foundering of arc roots.**

The North and South American Cordilleran orogenic systems extend for over 15,000 km along their western plate margins and developed above eastward-subducting oceanic plates (Fig. 1). Such systems comprise of the forearc (including the accretionary wedge and forearc basin), arc, and the strongly deformed hinterland and retroarc thrust belt; ancient counterparts are abound in the geological record[1,2]. These systems are distinguished from other plate boundaries associated with subduction zones by their large amounts of crustal shortening and thickening, high regional elevations and large linear batholith belts[1,3–5]. A correlation exists between rapid upper-plate motion towards the trench and large-magnitude retroarc shortening[6], although other modulating factors are important on a regional scale[6,7]. In this review, we focus on cyclical behaviour within Cordilleran orogenic systems that begins to operate once a contractional regime is established.

Important processes operating in Cordilleran systems include regional crustal shortening and associated sedimentary basin development, local crustal extension, widespread intermediate and silicic magmatism, and regional and contact metamorphism[8–13]. In the upper mantle beneath the magmatic arc, build-up of lithospheric and gravitational foundering of dense bodies of eclogite[14–17] is an important process of mass transfer between the upper-plate lithosphere and the mantle. Although all of these processes are well understood in their own right, any holistic model for Cordilleran orogenic systems must explain the potential links and feedbacks among them.

Estimates of shortening in Cordilleran retroarc thrust belts range up to ~400 km (refs 12,13,18–21). As these thrust belts consist almost exclusively of upper-crustal rocks that were detached from the lower-crustal basement and transported towards the foreland region[22–24], a slab of lower crust and lithosphere equal in length to the total upper-crustal shortening must have been underthrust beneath the hinterland and magmatic arc[25]. In the central Andes, the volume of lithosphere underthrust beneath the magmatic arc since early Cenozoic time is on the order of $10^7$ km$^3$. The fate of this vast amount of continental lithosphere is not accounted for in dynamic models of Cordilleran orogenic systems, which instead focus on processes driven by the subducting oceanic slab and mantle wedge[26–31]. Moreover, the variable rates at which this underthrusting occurs, and highly cyclical changes in apparent flux and isotopic compositions of arc magmas (Fig. 2) are not explained by changes in the convergence rate, the subducting oceanic slab or processes in the mantle wedge beneath the arc[32].

Recent studies of upper-mantle structure and dynamics beneath Cordilleran orogenic systems in North and South America demonstrate episodic gravitational foundering of dense bodies beneath Cordilleran magmatic arcs[15,33,34]. The volumes and rates of foundering are comparable to rates of mass transfer by underthrusting on the retroarc side of the system, raising the prospect that upper-plate processes are linked from the retroarc thrust belt to the forearc and upper mantle beneath the arc. Although subduction processes certainly are important for the evolution of Cordilleran orogenic belts[35], we emphasize the complex array of upper-plate processes that are required to accommodate retroarc mass transfer, as well as the potential feedbacks and links among these processes.

## Links and feedbacks among Cordilleran orogenic processes

Island-arc magmatism is driven primarily by hydrous melting of the convective mantle wedge above subducting slabs[36,37], as exemplified by primitive island arcs that accumulate mantle-derived basalts at a rate of 30 (±10) km$^3$ Myr$^{-1}$ per kilometre length of arc[38]. This rate is informally referred to as one Armstrong unit (1 AU) and represents the average melt productivity of the mantle wedge during subduction (the term was coined at the 2006 Geological Society of America Penrose Conference on arc magmatism in Valdez, Alaska, in honour of R. L. Armstrong). In contrast, the average composition of the upper 30 km of a Cordilleran-type arc is that of a low silica granodiorite, with relatively minor mafic rocks[15,39]. Although up to 50% of the mass composing Cordilleran arcs must be derived from melting of the convective mantle wedge above subducting slabs[36,37], as indicated by mafic rocks in these arcs[40] and required by heat budget considerations, the remainder is derived from the continental lithosphere[15]. Underthrust continental lithosphere provides

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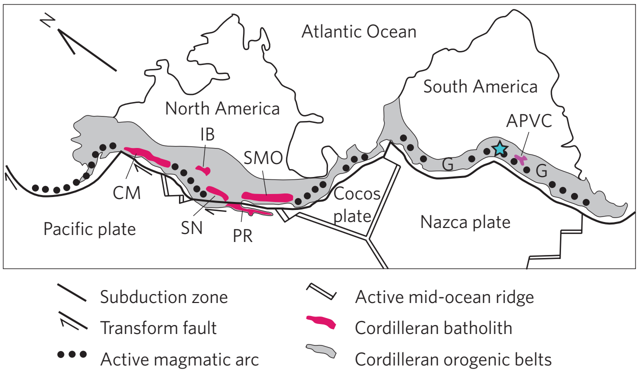


**Figure 1 | Key features of the North and South American Cordilleran orogenic belts**[5]. Much of the North American western plate margin is no longer an active subduction zone, whereas the entire South American western plate margin is active. Major batholiths in the North American Cordillera are as follows: CM, Coast Mountains; IB, Idaho-Boulder; SN, Sierra Nevada; PR, Peninsular Range; SMO, Sierra Madre Occidental. The star in the South American Cordilleran orogenic belt indicates the region in Bolivian Altiplano where rapid surface uplift during the late-Miocene has been documented[55]. APVC is the Altiplano-Puna volcano complex; G indicates gaps in the active Andean magmatic arc. The map projection is Mercator, with pole located at 25° N, 15° E (ref. 5).

the required continental material, and is a significant source of Cordilleran batholiths[32]. Thus, the rate of underthrusting — roughly equivalent to **[AU: Ok instead of 'proxied'?]** the rates of shortening in the retroarc thrust belt — is a limiting factor in the development of Cordilleran magmatic arcs.

Unlike island arcs, Cordilleran arcs record high-flux episodes (HFE's) separated by magmatic lulls[8,27,41–43]. The HFE's generate up to 75–80% of the arc mass within periods of 10–15 Myr, and their peaks are separated in time by approximately 25–50 Myr (Fig. 2). Magmatic addition rates in the upper-middle crust are about 3–4 AU during HFE's and around 0.8–1 AU during lulls[39,43]. Correlations between magmatic fluxes and rates of plate convergence or plate margin obliquity are not obvious in the available data[7,43], and there is no indication that the mantle wedge can become significantly more fertile during HFE's[32]. A reasonable conclusion is that the 1AU baseline flux **[AU: Ok?]** in Cordilleran arcs represents 'background' contributions from the mantle wedge, whereas the bulk of what forms during HFE's represents contributions from the continental plate or the subducting oceanic slab. However, isotopic and volumetric constraints, as well as thermal arguments, rule out large contributions from the slab and forearc[32]. Initial Nd isotopic composition ($\varepsilon_{Nd}$) **[AU: Please confirm definition of $\varepsilon_{Nd}$]** values for plutons ranging in composition from gabbro to granite in several well-documented Cordilleran arcs correlate strongly with $\varepsilon_{Nd}$ values **[AU: Ok?]** of local basement rocks[26,42,44]; HFE's are strongly correlated with Nd isotopic 'pull-downs' towards more evolved compositions, whereas magmatic lulls are associated with Nd isotopic 'pull-ups' (Fig. 2)[27,43]. Together these observations suggest that the temporally regular HFE's in Cordilleran arcs are fuelled by underthrusting melt-fertile continental lithosphere from the retroarc region, superimposed on the background magma flux from the mantle wedge. In addition, HFE's may be augmented by thermal weakening of the lithosphere in some arcs, which can promote large-scale convection of melt-rich lower crust into the upper crust[45].

Recent seismic[46,47] and geological[48,49] studies show that felsic rocks beneath long-lived continental arcs of North America are ~30 km thick, which requires a large, dense residual mass (the arc 'root', as opposed to a buoyant crustal root). The ratio of residual mass to melt mass in an arc batholith is 1:3 (ref. 15), depending on the bulk composition of the arc. Experimental petrologic studies[50–52] and direct evidence from exposed arc terranes and deep lithospheric xenoliths[34] show that the residue of these arcs is granulitic at pressures below ~15 kbar, and becomes a dense (~3.6 g cm$^{-3}$), bi-mineralic garnet pyroxenite (eclogite) at higher pressures (deeper levels). These dense residues are prone to foundering into the upper mantle over the entire life of the arc[43]. Thus, the link between retroarc underthrusting and arc magmatism also has implications for processes in the upper mantle.

Growth and removal of dense arc roots strongly affects the dynamics of the entire orogenic system. Root growth exerts negative feedback on further underthrusting, owing to the limited space between the strong subducting slab and the upper plate[53]. Evacuation of the eclogitic root beneath the arc will open space for renewed rapid underthrusting on the retroarc side, and possibly flat-slab subduction on the forearc side. Growth of a dense arc root also exerts a negative buoyancy force on the arc and the hinterland region, whereas isostatic adjustment following root removal may produce a rapid increase in surface elevation[54,55]; in turn, this will increase the surface slopes of the forearc and retroarc regions (Fig. 3). Maximum principal stress may rotate from horizontal to vertical in the hinterland[54], leading to upper-crustal extension.

Changes in the surface elevation will also alter the taper of forearc and retroarc orogenic wedges (Fig. 3a), which in turn results in forward propagation of the wedge (supercritical taper) or internal shortening (subcritical taper)[56–58]. A modest 1 km isostatic uplift event in the hinterland of a 100–200-km-wide thrust belt would produce a 0.28–0.57° increase of surface slope, driving the retroarc wedge into a supercritical state (Fig. 3b). A foreland flexural-wave forms in response to the weight of the growing orogenic wedge and migrates in front of the thrust belt at a rate that decreases or increases depending on whether the wedge is propagating rapidly (supercritical) or slowly (subcritical) (assuming constant convergence rate). The sediment accumulation rate in the foreland basin will reflect the velocity of the flexural wave.

In the forearc, the amount of sediment entering the trench strongly affects wedge morphology and dynamics[59–61]. Sediment-rich forearcs are characterized by accretionary prisms that produce bathymetric highs between the trench and the arc, and thereby promote the development of forearc basins[62]. Sediment starvation inhibits the development of accretionary wedges and forearc basins, and promotes the subduction erosion of forearc crust at the trench[61–63].

The response of the forearc orogenic wedge to changes in hinterland elevation depends on sediment volume in the trench. Critical taper in a sediment-rich forearc wedge can be maintained by self-similar growth of the wedge, which enhances the forearc topographic high and sediment accumulation in the forearc basin. In a sediment-starved forearc, stable sliding neither adds nor removes significant material from either plate. In both sediment-rich and sediment-starved forearcs, subcritical taper promotes internal deformation and thickening in order to increase taper. Supercritical taper in a sediment-rich forearc forces the wedge to propagate forward, and the resulting addition of material to the accretionary prism will increase flexural subsidence and sediment accumulation in the trench and forearc basin. In a sediment-starved forearc the need to elongate the wedge in the absence of new material into which it might propagate is accommodated by internal extension and mass wasting into the trench, which in turn may enhance subduction erosion (Fig. 3a)[63].

All of these processes in Cordilleran orogenic systems — retroarc underthrusting, arc magmatism, arc-root foundering, changing surface elevation and orogenic-wedge dynamics, and development/disruption of sedimentary basins — are interrelated, and must operate according to physical and chemical laws that govern material properties and mass transfer.

## A unifying model

We propose a conceptual model for the long-term evolution of Cordilleran orogenic systems that integrates apparently disparate temporal variations in retroarc and forearc kinematics, foreland flexural-wave migration, magma flux and composition, eclogite formation and subsequent removal, and hinterland elevation gain and extension (Figs 3 and 4). Once a two-plate, strongly convergent retroarc system is established, shortening begins to feed continental lower crust and mantle into the region below the magmatic arc (Fig. 3c), which up to this point is characterized by low flux and ocean-island-arc composition. Upper-crustal sedimentary rocks are scraped off the underthrusting continental plate to form the retroarc thrust belt, which drives a wave of flexural foreland basin subsidence through the continental lithosphere at a rate equal to the sum of the shortening and thrust-belt propagation rates[64]. An influx of melt-fertile lower crust and mantle lithosphere beneath the arc initiates a HFE in the arc. We suggest that the heat necessary to produce these melts is already supplied by upward migration of hot hydrous melts from the asthenosphere plus or minus radiogenic heating, and that the trigger for the HFE is the increased supply of hydrous continental lithosphere rather than any change in the architecture or dynamics of the system. HFE's would not be expected in subduction systems that are not strongly convergent.

Melting beneath the arc begins to differentiate a dense restitic granulite and garnet pyroxenite (eclogite) in the lower crust and mantle lithosphere (Fig. 3d). High-flux events are clearly synchronous with root development; systems that produce thick batholiths, in some cases >30 km thick[43], are almost certain to develop a root that is denser than the underlying mantle[15]. Consequently, delamination of the lower crust and the upper mantle lithosphere will take place after, not before, HFE's (Fig. 4a). This timing is also supported by the negative excursions in $\varepsilon_{Nd}$ values during HFE's. Magmas derived from the underthrusted continental material become increasingly evolved as exemplified by the $\varepsilon_{Nd}$ isotopic pull-down (Fig. 4a). Build-up of lithosphere beneath the arc exerts negative feedback on continued retroarc shortening, and the growing eclogite exerts a negative buoyancy force on the upper plate, paradoxically decreasing surface elevation in spite of continued shortening and crustal thickening (Figs 3d and 4c). Subcritical taper causes internal shortening and disruption of the forearc basin in sediment-rich forearcs, and out-of-sequence thrusting in the retroarc wedge (Fig. 3a, d). The stage is now set for the second phase of the model.

Attainment of critical mass in the growing eclogitic root results in a foundering event (Fig. 3e)[53,65,66]. Removal of large volumes of dense lithosphere from beneath the arc and influx of asthenospheric heat causes a rapid isostatic increase in surface elevation and ignimbrite eruptions[44] (Fig. 3e). Magmatism soon returns to background flux-rates and relatively primitive isotopic compositions (the isotopic pull-up) due to the proximity of the asthenosphere directly below the reconfigured arc Moho[44,65] and the absence of melt-fertile lithosphere. Rapid uplift and increased gravitational potential energy may rotate maximum principal stress from horizontal to vertical, so that the upper crust in the arc and the thrust-belt hinterland is thrown into extension[54,67]. Catastrophic, locally fault-controlled caldera-collapse eruptions[44] may take place at the surface (Fig. 3e). Increased hinterland elevation also causes both forearc and retroarc orogenic wedges to become supercritically tapered and propagate forward. Taper increase in the forearc enhances forearc basin accumulation in a sediment-rich setting, and forearc extension and subduction erosion in a sediment-starved setting. Simultaneously, relief of the room problem beneath the arc by root foundering allows the cycle to begin anew, with rapid underthrusting of retroarc continental lithosphere, propagation of the retroarc thrust belt towards the craton, and flexural-wave migration through the foreland. Eventually, regional elevation declines as retroarc underthrusting rejuvenates the supply of melt-fertile lithosphere and the arc root begins to reform over the ensuing 20–30 Myr (Figs 4c). Crustal shortening and magmatic flux are out of phase (Fig. 4a, b).

The duration of magmatic lulls between HFE's is controlled by the amount of time required for retroarc underthrusting to replenish melt-fertile lithosphere sufficient to trigger a new HFE. Additional lag time may result from thermal inertia. The tempo of HFE's is thus controlled by the rate of retroarc shortening: rapid shortening supplies more melt-fertile material to the system, which produces greater volumes of melting, which increases rates of granite and eclogite production, and causes more rapid attainment of critical mass in the arc root, culminating in more frequent dripping or delamination.

This model does not explicitly incorporate episodes of flat-slab subduction, which are common in Cordilleran orogenic

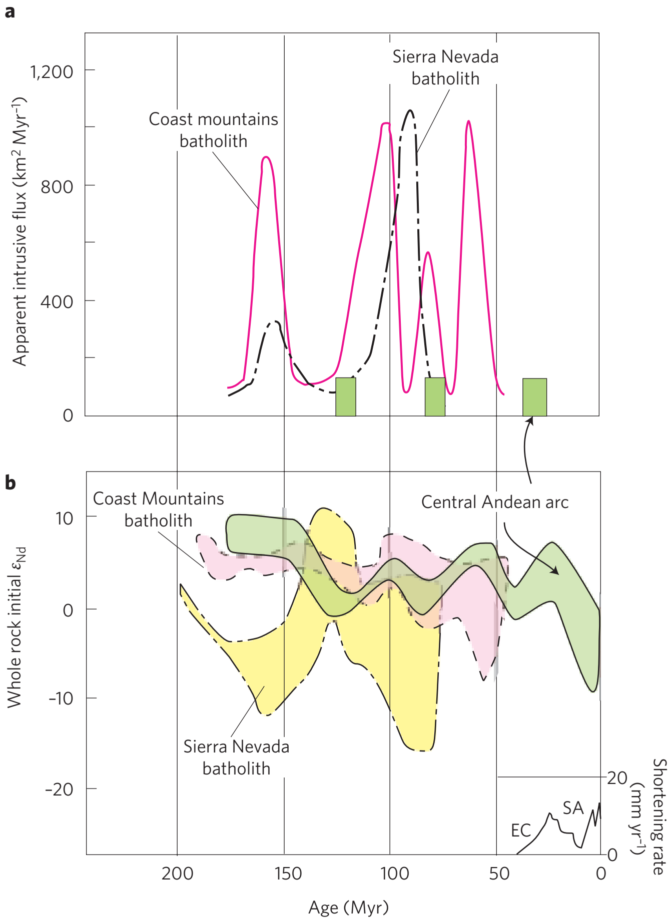


**Figure 2 | Magmatic histories of Cordilleran arcs. a,** Apparent flux rates for the Coast Mountains batholith[32,71,72] and the Sierra Nevada batholith[43] versus crystallization age. The green boxes show the timing of magmatic lulls in the central-Andean arc[27], where flux rate is not available. **b,** Whole rock initial $\varepsilon_{Nd}$ values versus crystallization age for the Coast Mountains batholith[32,83], the Sierra Nevada batholith[43] and the central-Andean magmatic arc[27]. Inset: Subandean (SA) and eastern Cordilleran (EC) shortening rates in the central Andes[7].

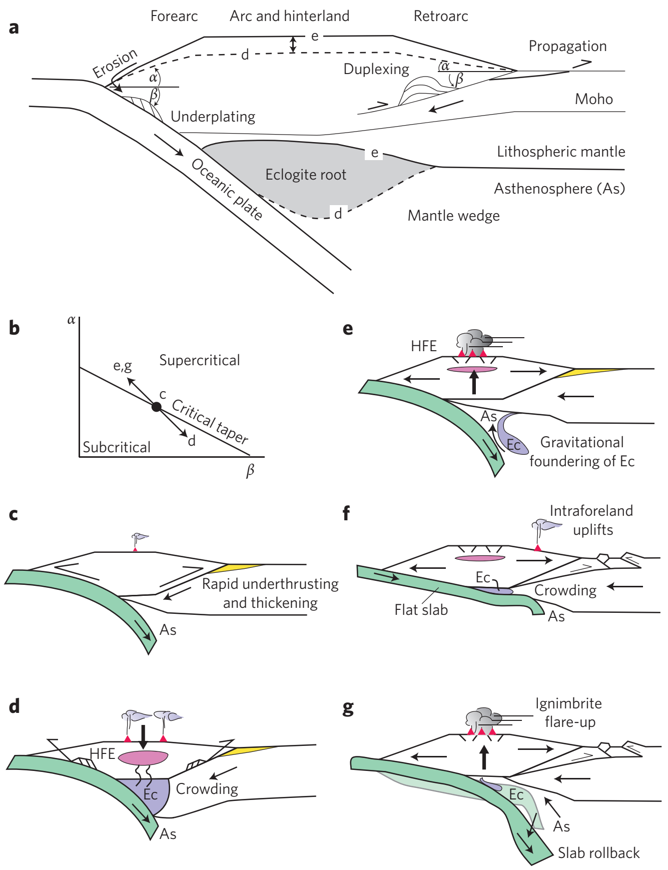


**Figure 3 | Evolution of Cordilleran orogenic systems. a,** Schematic cross-section (not to scale) of a Cordilleran orogenic system with a sediment-starved trench, illustrating the effects of eclogite root development and removal on isostatic and orogenic wedge taper ($\alpha + \beta$). For clarity, the magmatic arc is omitted. All lettered labels refer to other parts of this figure. Dashed lines labelled d represent the topographic profile and Moho configuration at the peak of eclogite (gray shading) growth. Solid lines labelled e show post-drip/delamination configurations, in which the Moho is adjusted upward and the surface has rebounded to high elevation. Kinematic processes responding to changes in orogenic wedge taper (duplexing and underplating) are also illustrated. **b,** Critical taper diagram in terms of surface slope ($\alpha$) and the angle of the basal detachment ($\beta$) depicting the evolution of taper in forearc and retroarc orogenic wedges at different stages of the cycle. The dot labelled c represents a given orogenic wedge at the critical taper (the straight line with negative slope), and arrows indicate taper changes corresponding to configurations labelled in part **a,** and illustrated in cross sections **c**–**g** of this figure. **c**, Retroarc underthrusting. **d**, Development of an arc HFE and growth of the eclogite root (Ec) beneath the arc causing a regional isostatic depression of surface elevation, and internal underplating and duplexing in the forearc and retroarc wedges. **e,** Eclogite root foundering, regional uplift and outward propagation of the flanking orogenic wedges, upper-crustal extension and ignimbrite flare-up. Subduction of a buoyant oceanic slab immediately after stage **e** would potentially produce the situation illustrated in **f,** where flat-slab subduction creates crowding beneath the arc and drives strain into the foreland region. As the slab returns to a normal subduction angle **g,** upwelling asthenosphere (As) may promote a regional ignimbrite flare-up.

settings[68–70] and have been called on to explain some of the phenomena illustrated in Fig. 3 (refs 27,71). Flat-slab subduction terminates or drives arc magmatism towards the continental interior (Fig. 3f)[71–74], and disrupts the trench[63], forearc basin[75] and retroarc foreland[73,76]. In so far as flat-slab subduction is caused by anomalously buoyant oceanic crust entering the subduction zone[70], no inherent spatial–temporal relationship exists with the Cordilleran cycle as portrayed here. In the case of buoyant oceanic lithosphere entering the trench at the peak of a HFE, the growing arc root may force the slab to flatten at a deeper level[75]. The buoyant slab may prop up the eclogitic root and prevent delamination/dripping (Fig. 3f)[33,75]. A post-drip/delamination configuration beneath the magmatic arc is conducive to shallow flat-slab subduction and arc shut-down, such as proposed to explain late Miocene shut-downs in the Andean arc in Peru and central Chile (Fig. 1)[71,73]. Flat-slab subduction should exacerbate lithospheric crowding beneath the arc, increasing differential stress to the point of failure within the cratonic basement >1,000 km from the trench and leading to inboard basement-involved foreland deformation (Fig. 3f)[72,73]. Simultaneously, decreased retroarc shortening due to extreme crowding above the flat slab should increase strain in the forearc region. Slab steepening after the anomalously buoyant oceanic lithosphere has passed through the subduction system may lead to catastrophic regional ignimbrite eruptions such as those that took place during the mid-Cenozoic after the Laramide event in the western US. (Fig. 3g).

Eclogitic root production and foundering beneath the Sierra Nevada batholith are well documented[33,34], and provide an example of what may happen when flat-slab subduction interrupts the proposed Cordilleran cycle. Onset of Laramide flat-slab subduction soon after a HFE at 90–100 Myr ago partially preserved the arc root until resumption of normal-angle subduction and opening of the slab window after the East Pacific spreading centre began to collide with the western continental margin around 30 Myr. Xenolith and seismic studies demonstrate the existence of a garnet pyroxenite root beneath the Sierra Nevada during the Miocene, and its removal from the southern part of the range between 10 and 3 Myr[33]. Receiver-function and tomographic imaging show that the root is delaminating from beneath the eastern side of the Sierra Nevada and flowing into an upper mantle drip beneath the southern San Joaquin Valley[77]. Constraints from xenoliths, volcanism and geodynamic modelling[78] suggest that foundering initiated around 25 Myr with the onset of basin and range extension, but the actual delamination event in the central and southern Sierra Nevada only began ~5 Myr and continues in the central part of the range[79]. A large body of dense pyroxenite remains in place beneath the low-lying central-western foothills, where earthquakes in the lower crust indicate localized stresses. In contrast, the eastern side of the Sierra Nevada is underlain by a sharp and shallow Moho, suggesting that wholesale delamination can occur within 5–10 Myr.

## Testing linked cyclicity

Although data sufficient to comprehensively test this model over several cycles within a single Cordilleran orogenic system are only beginning to accumulate, aspects of the model are supported in parts of the North and South American Cordilleras. High-flux events are recorded in the Sierra Nevada batholith during the Late Jurassic (160–150 Myr) and Late Cretaceous (100–90 Myr) periods (Fig. 2)[43]. These HFE's are documented throughout the Sierra Nevada batholith, despite different levels of exposure (from palaeo-calderas to >30 km palaeo-depths[80]). Each HFE was accompanied by an isotopic pull-down, and followed by an isotopic pull-up. The 90–100 Myr HFE was followed immediately by hinterland extension[11,67,81], an episode of supercritical taper and rapid eastward propagation of the Sevier thrust belt[12,81], and regional thrust-belt erosion[58]. The Late Jurassic HFE was also followed by abrupt eastward propagation of the thrust front[81]. Our model explains these observations by removal of eclogitic arc roots created during HFE's and associated isostatic rebound in the thrust-belt hinterland. The two HFE's were generated by preceding periods of rapid underthrusting, during the Middle Jurassic[82] and the Early Cretaceous[12]. The predicted HFE following the Late Cretaceous thrust propagation event was interrupted by Laramide flat-slab subduction and mid-Cenozoic cessation of subduction along the western plate margin.

Recent studies in the Coast Mountains of western British Columbia confirm a cyclical granitoid production record with peaks at ~155–140, ~120–100, ~80–70 and ~60–50 Myr (Fig. 2)[32,42,83,84]. Each HFE is associated with an isotopic pull-down. Seismic receiver-function studies in this region reveal a distinct Moho at ~35 km depth, possibly created by delamination and foundering of a dense batholithic root[85]. Surface-wave imaging confirms that the upper mantle beneath western British Columbia moves very slowly**[AU:OK?]**[85] — consistent with a shallow asthenosphere and thin mantle lid developing after a recent delamination event. As predicted by the general model, major retroarc shortening events[86] lagged behind the 155–145, 120–100, 80–70, and 60–50 Myr HFE's.

In the central Andes (15–25° S) episodic arc magmatism is characterized by progressively more compositionally evolved HFE's[26,27,71] peaking at ~130, 80, 40, and <10 Myr (Fig. 2)[27]. Major eastward jumps in the deformation front occurred at ~38–35 and ~10–8 Myr[20,87–90], possibly in response to hinterland elevation gain following arc root removal[55]. The ~8 Myr event began coevally with inferred hinterland elevation gain in the Bolivian Altiplano[55,91]. Seismic studies indicate a zone of partial melt in the middle crust beneath the southern Altiplano/northern Puna plateau, coincident with widespread voluminous ignimbrites of the 10–1 Myr Altiplano-Puna volcanic complex (APVC; Fig. 1)[44,92–94]. It has been suggested that the APVC is the erupted counterpart of the mid-crustal low-velocity body, which represents the batholith-size partial melting zone of a modern arc HFE[44]. Major crustal shortening — required by our model to fuel this HFE — commenced 25–20 Myr earlier during development of the eastern Cordillera thrust-belt (Fig. 2 inset)[90,95]. Evidence for recent removal of seismically fast lithosphere beneath the central-Andean arc is abundant in seismic tomographic studies[53,66,96]. Higher regional elevation (~4.1 km) and topographic relief in the Puna plateau compared with the Altiplano (~3.7 km) to the north[3], coupled with the presence of large late-Cenozoic sedimentary basins and evidence for late-Miocene rapid elevation gain in the northern Altiplano[55,91], suggests that the Puna plateau experienced delamination only since ~3 Myr, whereas the Altiplano may have already begun the next cycle of eclogite build-up. More recent delamination beneath the Puna plateau is supported by petrologic studies of young basalts, which are attributed to melting of remnant continental lithosphere after partial delamination[65,97].

The frequency of documented HFE's in Cordilleran batholiths ranges between ~50 and 25 Myr (Fig. 2), and seems to correlate with shortening rates in associated retroarc thrust belts. For example, HFE's in the central-Andean arc, where the retroarc shortening rate is ~7–8 mm $yr^{-1}$ (refs 20,98), have a frequency of 25–40 Myr, whereas HFE's in the western US have a frequency of ~50 Myr and are associated with a retroarc thrust belt that shortened at a rate of only ~3–5 mm $yr^{-1}$ (ref. 12). In the central-Andean arc, the frequency of isotopically inferred HFE's increases with time (Fig. 2), suggesting that the rate of supply or melt fertility of underthrusting South American lithosphere may have increased over time. Long-term trends towards more evolved isotopic compositions are evident in all Cordilleran batholiths (Fig. 2), indicating supply of older cratonic material through time[9,42].

Although each example discussed here is broadly consistent with the model, numerous questions persist regarding the details for any given orogenic belt. The effect of accreted terranes could be profound, as in the North American Cordillera[5] and the northern

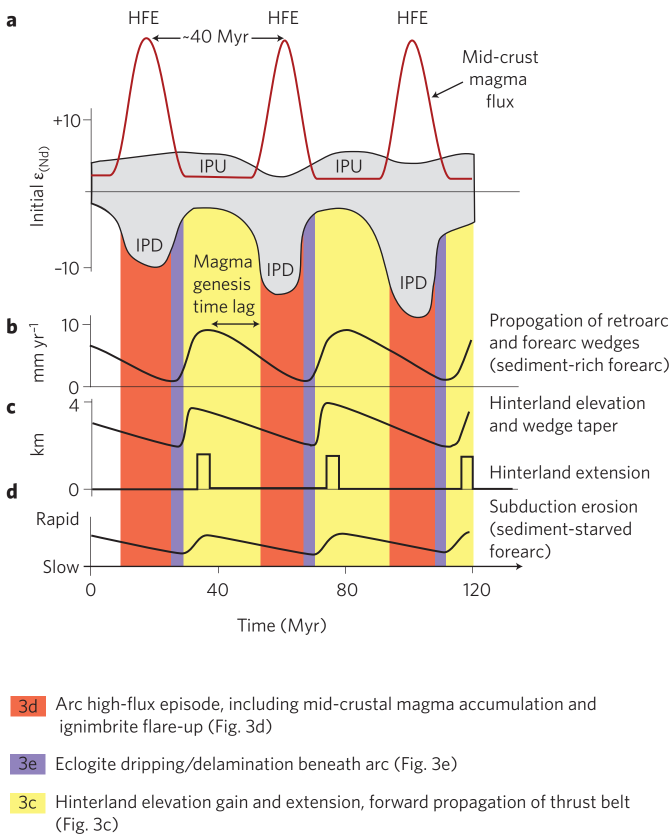


**Figure 4 | Temporal evolution of key processes and responses in the Cordilleran cycle**. The figure is cross-referenced to Fig. 3**c**–**e**. In all plots, time passes from left to right. **a,** Arc magma flux plotted against the backdrop of isotopic composition in terms of the initial $\varepsilon_{Nd}$ value (grey area), showing coincidence of isotope pull-downs (IPD) and pull-ups (IPU) with high-flux and low-flux events, respectively. Note increasingly negative $\varepsilon_{Nd}$ values during IPD's, reflecting underthrusting of progressively older cratonic material. **b,** Rate of propagation in the retroarc thrust belt and (for a sediment-filled trench) forearc accretionary prism. **c,** Change in hinterland surface elevation and coincidence of upper-crustal extension events with peaks in surface elevation. **d,** When the trench is sediment-starved the primary response in the forearc is in terms of relatively rapid or slow subduction-erosion. The ~40 Myr cyclicity is based on Fig. 2.

Andes[99]. Nevertheless, magmatism in the Coast Mountains batholith belt, where terrane accretion is most evident, shows typical Cordilleran periodicity[83]. Temporal changes in plate vectors, along-strike variations in plate convergence, spatial variations in sediment supply to the trench, lithologic composition and age of the underthrusting continental lithosphere, lateral crustal flow, and possible dynamic processes in the mantle related to subduction angle[100] must also affect the operation of the cycle. Delamination of lithosphere due to phase changes in the absence of magmatic processes[17] could also exert a strong control on mass redistribution in Cordilleran systems. Notwithstanding these and other potential complications, Cordilleran magmatic arcs and retroarc thrust belts show linked, cyclic behaviour requiring voluminous melting of the underthrusting continental plate; disposal of a large fraction of this material into the mantle beneath the arc seems inescapable[14,15]. Our model proposes a plausible set of interrelated mechanisms (Fig. 4) to accomplish this process and may be readily tested and refined in Cordilleran orogenic systems with data from structural geology and basin evolution, petrology and geochronology, thermochronology, palaeoaltimetry, seismology, and geodynamic modelling.

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