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Intra-oceanic subduction shaped the assembly of Cordilleran North America

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The western quarter of North America consists of accreted terranes—crustal blocks added over the past 200 million years—but the reason for this is unclear. The widely accepted explanation posits that the oceanic Farallon plate acted as a conveyor belt, sweeping terranes into the continental margin while subducting under it. Here we show that this hypothesis, which fails to explain many terrane complexities, is also inconsistent with new tomographic images of lower-mantle slabs, and with their locations relative to plate reconstructions. We offer a reinterpretation of North American palaeogeography and test it quantitatively: collision events are clearly recorded by slab geometry, and can be time calibrated and reconciled with plate reconstructions and surface geology. The seas west of Cretaceous North America must have resembled today's western Pacific, strung with island arcs. All proto-Pacific plates initially subducted into almost stationary, intra-oceanic trenches, and accumulated below as massive vertical slab walls. Above the slabs, long-lived volcanic archipelagos and subduction complexes grew. Crustal accretion occurred when North America overrode the archipelagos, causing major episodes of Cordilleran mountain building.

Continents grow through subduction magmatism and collision of arcs and other buoyant crustal fragments at their margins. Poorly understood, such collisions are of broad scientific interest because they cause rapid geographic changes, affecting climate, ocean circulation, biota and the formation of economically important metal deposits. North America was enlarged by a sequence of massive terrane collisions relatively recently (between 200 million years (Myr) ago and 50 Myr ago), which created the mountainous Cordillera of the American West[1].

Reconciling geological records on land with those of the ocean basins has proved difficult. Magnetic stripes on the sea floor are the basis of all quantitative plate tectonic reconstructions, and well-preserved Atlantic spreading records indicate that North America has moved westward continuously since the breakup of Pangaea (about 185 Myr ago), away from Africa and Europe[2]. In contrast, more than half of the seafloor records of proto-Pacific (Panthalassa) ocean spreading are missing. The Pacific plate records the existence of another major oceanic plate to its northeast since at least 180 Myr ago: the Farallon plate. This plate is usually assumed to have filled the eastern Panthalassa basin, extending to the western margin of North America and subducting under it, although this is not required by the magnetic seafloor data. Hence, the Farallon plate, invoked as the causative agent in almost all major land geological events since late Jurassic times[2,3], should also have transported the terranes to the continental margin.

However, dozens of terranes have accreted to North America since 200 Myr ago[1], but not to the Andean margin of South America, supposedly a closely analogous setting. The terranes are mostly Triassic to Cretaceous island arc–subduction assemblages, but include three more heterogeneous superterranes: Intermontane (IMS)[4,5], Insular (INS)[4] and Guerrero (GUE)[6], which are essentially microcontinents. Their exact origins remain mysterious, but the terranes formed at various latitudes and times, as inferred from palaeomagnetic observations and fossil faunas, and pre-assembled at others. This implies the temporary existence of additional oceanic plates in the northeastern proto-Pacific Ocean[7,8], which are missing from quantitative plate reconstructions.

The mantle retains a memory of ancient plate configurations, in the form of subducted slabs, which body-wave tomography images *in situ* as domains of faster-than-average seismic wave velocities. Beneath North America these slab relics are massive, almost vertical walls extending from 800 to 2,000 km in depth, and typically 400–600 km wide (Fig. 1, Supplementary Fig. 1). The largest wall runs from northwest Canada to the eastern USA and on to Central America, and has been called the Farallon slab, one of the most massive features in global tomographies[9–12]. We argue that in fact most of this slab wall is not Farallon and subdivide it into the Angayucham (ANG), Mezcalera (MEZ) and the Southern Farallon (SF) components (Fig. 1b). This reinterpretation is based on our most recent tomography model[13], which utilizes dense USArray data[14] in addition to global network data, using a cutting-edge waveform inversion method: multiple-frequency P-wave tomography[13,15].

Besides putting the known eastern slab walls[9–12] in sharper focus, we discovered[15] that another, more westerly slab wall, the Cascadia Root (CR in Fig. 1b, depth 700 km to more than 1,800 km), connects upward continuously to the present-day Cascadia trench, into which the last remnant of the Farallon (Juan de Fuca) plate is subducting. This makes CR a Farallon slab by definition, and prompted us to re-evaluate whether MEZ/ANG/SF do really constitute subducted Farallon Ocean floor, which to our knowledge has never been questioned.

For plate reconstructions, the crucial question is whether (and how) these lower-mantle slab walls have moved laterally since they were deposited beneath their corresponding volcanic arcs (past versus present x–y positions in an absolute reference frame). Here we quantitatively test the hypothesis that they have not moved appreciably, that is, there has been only vertical sinking within our observational uncertainties (a few hundred kilometres laterally). Motivated primarily by imaged slab geometries, this null hypothesis also seems sensible in light of the Cenozoic subduction record, where absolute trench motion on average contributed only 10–30% of total plate convergence[16,17].

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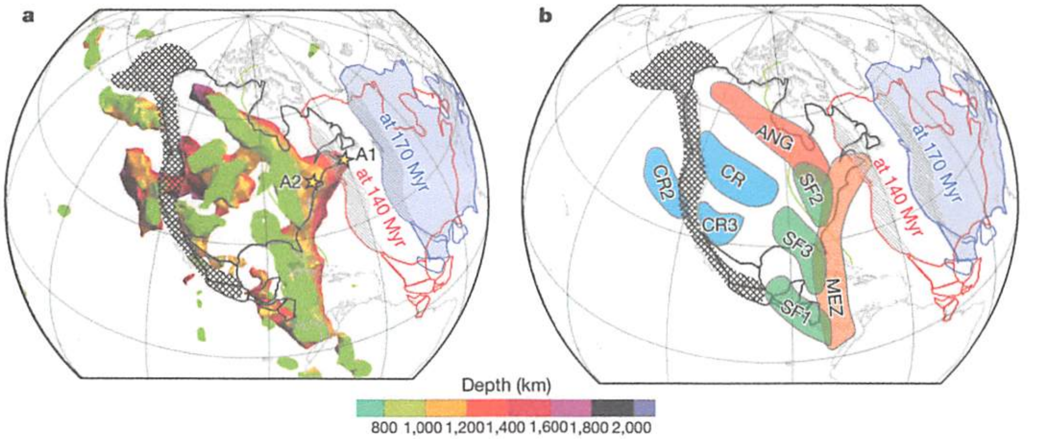

Figure 1 | Slabs under North America and continental motion over time. **a**, Subducted slabs at and below 900 km depth. P-wave tomography model[13] rendered as three-dimensional (3D) isosurface contours, which enclose faster-than-average structure (threshold $\mathrm{d}v_P/v_P = 0.25\%$, where v_P is the P-wave velocity). Colour signifies depth and changes every 200 km; the scene is illuminated to convey 3D perspective. At a sinking rate of about 10 mm yr^{-1}, this slab assemblage should have been deposited from about 200 Myr ago to 90 Myr ago. Reconstructed continent positions at 140 Myr ago are shown in a hotspot reference frame[21] and at 170 Myr ago in a hotspot/palaeomagnetic hybrid frame[22]. The hatched area represents location uncertainty for continental margin during Jurassic/Cretaceous times; the cross-hatched area shows terranes that accreted during Cretaceous and early Tertiary times. **b**, Interpretative legend. The slab walls divide into four groups: Cascadia/Northern Farallon slabs (blue) and Southern Farallon slabs (green), owing to eastward subduction; Angayucham (ANG, red) and Mezcalera (MEZ, orange) slabs, owing to westward subduction. Before 140 Myr ago, sizeable ocean basins separated North America from the ANG/MEZ trenches.

Slabs and arcs at stationary trenches

Figure 2a and b shows how a steep, widened slab wall could be piled up by nearly vertical sinking beneath a long-lived, stationary trench and volcanic arc. An Andean-style west-coast trench could not have been stationary because North America moved westward as the Atlantic Ocean spread. This contradiction is resolved by westward intra-oceanic subduction before the arrival of the continent, followed by a polarity switch of subduction to its current eastward motion into a continental-margin trench (Fig. 2c). Such a scenario implies that the imaged lower-mantle slabs MEZ/ANG/SF are Jurassic to Cretaceous in age, allowing the collision of North America with their subduction zones to cause the Cretaceous terrane accretions.

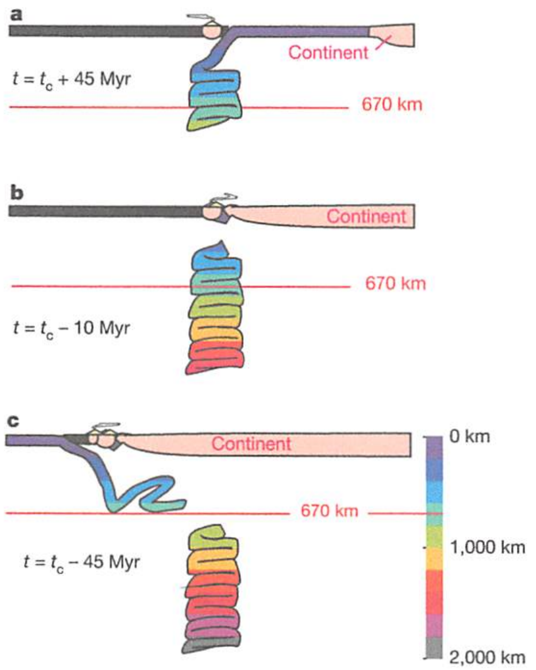

Figure 2 | Schematic cross-section and evolution of a terrane station. t_c denotes the time of arc-continent collision. Motions are shown in a lower-mantle reference frame. **a**, Well before the collision, both trench and arc are active. Slab buckling is due to the viscosity contrast around 670 km, but the backlog reaches into the upper mantle. **b**, Around t_c and up to about 10 Myr later, the continent overrides the trench and accretes its arc terranes, while the slab breaks. **c**, Well after the collision, the slab wall continues to sink. Seaward, a new Andean-style subduction has developed. Anchored in the lower mantle, the slab wall is sinking vertically at a steady-state rate of approximately 10 mm yr^{-1} in all three panels.

To the extent that slabs sink vertically, they record palaeo-arc and trench locations in an absolute sense. Thus, vertical sinking permits quantitative predictions of the location and timing of continent-trench collisions when tomography and absolute plate reconstructions are combined. These predictions can be tested against the docking times of arc terranes inferred from land geology. Abrupt upward truncations of the slab walls, which are well resolved tomographically (Supplementary Fig. 2), correspond to the shutdown of the overlying trench-arc systems, and hence to docking times (Fig. 2).

If the trench remains stationary, a vertical slab pile is deposited beneath it. If the trench moves (but every parcel of slab sinks vertically), the imaged slab will dip towards older trench locations, assuming no dramatic lateral variations in sinking rate. The observed lower-mantle walls are widened to 400–600 km laterally, that is, 4–6 times the thickness of oceanic lithosphere—this is not artificial blur, but the actual reason for their robust tomographic visibility[18]. Thickening is probably achieved by slab folding above the 670-km viscosity jump, deviations from vertical sinking being due mainly to the folding process itself (Fig. 2). In convection models, slab folding occurs preferentially beneath the kind of stationary trenches postulated here[18–20]. Massive, thickened slabs like these can be expected to be the drivers of 'mantle wind', rather than blowing in it: that is, if anything sinks vertically, it should be these slabs.

Such slab walls indicate that their overlying trenches remained in the same absolute locations for a long time, with arc and accretionary complex growth stationed above these locations. Observation of massive slab walls leads us to think of their associated, intra-oceanic trenches as 'terrane stations' where new crustal material is gathered to await transfer to a continental margin. Terrane stations above ANG and MEZ were not conveyed eastward into a continental Farallon trench. Rather, North America migrated westward, collided, and accreted the ANG and MEZ terrane stations. Hence slab walls tie the now-displaced terranes to a laterally unchanged subsurface, constraining absolute locations and temporal evolution of oceanic trenches more than a hundred million years after their demise.

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Figure 1 shows the reconstructed western margin of North America[21], together with schematic outlines of the lower-mantle slab walls from tomography[13]. North America's relative westward motion is well constrained by the Atlantic spreading record[2,22], independently of any absolute reference frame. Comparison to the basic geometry of ANG and MEZ suggests that these two slabs did not subduct beneath the continental margin: (1) the slabs are vertical from 800 to 2,000 km depth, indicating a stationary trench, whereas the margin moved westward continuously. (2) The outlines of ANG and MEZ, especially the pronounced eastward promontory of MEZ, do not match the outlines of the continental margin (Fig. 1). If continental subduction had controlled slab deposition, then slab curvature should reflect the curvature of the continent. (3) West of ANG/MEZ, the slab is smeared out laterally in the upper 800 km (Supplementary Fig. 1), as might be expected from a trench dragged along by a migrating continent: direct observational evidence for a switch in subduction mode after override, from stationary oceanic to migrating continental.

Quantitative prediction of arc accretion

Continent motions in Figs 1 and 3 are tied to an absolute hotspot reference frame[21] and rendered by the palaeo-geographic information system GPlates[23,24]. Like the vertically sinking slab walls, vertically rising plumes are thought not to have significant lateral motions relative to the lowermost mantle[25] (smaller deviations are correctable[21]), so that the hotspot and 'slab wall' reference frames are equivalent (no relative motion). In this merged reference frame, the lateral overlay of North America's reconstructed western margin with a slab wall amounts to a spatiotemporal prediction of trench override and terrane accretion.

For example, Fig. 1a shows the North American margin overriding point A1, eastern promontory of the MEZ arc, sometime before 140 Myr, probably around 150 Myr ago. Slab sinking velocities can be inferred: the shallow end of MEZ beneath A1 is seen to have sunk to a depth of approximately 1,500 km, implying an averaged sinking rate of 10 mm yr^{-1}. The MEZ promontory shallows to the southwest. This is unrelated to trench polarity (the slab did not dip northeastward), but rather reflects differential sinking times (subduction at A1 was choked off earlier than at A2). Sinking rates could be estimated from any well-resolved point on the upward truncation of a slab wall, but we choose five points A1–A5 that are associated with supporting evidence from land geology (Table 1 and Fig. 3). Predicted override ages are Jurassic–Cretaceous (146–55 Myr ago), becoming progressively younger westward, and truncation depths shallow to the west as expected. Sinking rate estimates range between 9 and 12 mm yr^{-1} (± 2 mm yr^{-1}), consistent with findings of 12 ± 3 mm yr^{-1} globally[12]. Figure 3 renders the override sequence in four time slices, each showing only slabs that should already have been deposited at the time, assuming the sinking rate was 10 mm yr^{-1} (the average of A1–A5 in Table 1).

The CR must be a Farallon slab because the Farallon (Juan de Fuca) plate is still subducting into it today[15]. Pacific seafloor records indicate continuous Farallon spreading since about 180 Myr ago[3,26], so that at a sinking rate of 10 mm yr^{-1}, the over-1,800-km-deep CR accounts for the entire lifetime of the (northern) Farallon plate. The presence of this CR slab implies that the equally deep and thickened ANG slab further east cannot represent Farallon lithosphere, as has been assumed[9,12,13,27,28]. Rather, the ANG slab must have dipped in the opposite direction (southwestward) in order to have sourced sufficient plate material from an ocean basin that lay to the northeast, the consumption of which accommodated the westward drift of North America. This scenario for transporting North America away from the former Pangaea provides an alternative to westward rollback of a continental Farallon trench.

Hence our inferred trench/plate evolution in Fig. 3 differs fundamentally from the commonly accepted scenario of MEZ/ANG as products of east-dipping, Farallon-beneath-continent subduction. Westward subduction of the ANG and MEZ slabs, probably since early Jurassic times, consumed the ocean that bounded North America on the west (the ANG and MEZ basins in Fig. 3). Both basins were consumed in a zipper-like fashion: MEZ closed from north to south, ANG from south to north, as North America gradually overrode and shut down the ANG/MEZ arcs between 150 and 50 Myr ago. Further west, the early Farallon Ocean subducted into two east–west-oriented Cascadia slabs (CR/CR2), but established additional segments SF1/SF2 after a clockwise rotation at about 147 Myr ago[22,26]. Thus at northerly latitudes, two long-lived terrane stations of opposite polarity coexisted in ANG and CR, a variant not considered in Fig. 2. Upon override, the east-dipping Farallon trenches started rolling back with North America. Moderate complexities in the Pacific–Farallon spreading record[3,26] probably reflect the transitions of individual trench segments from intra-oceanic to Andean-style.

Supporting evidence from land geology

We now use the terrane-station property of oceanic trench/arc systems to test archipelago override predictions made by tomography and plate reconstructions. The collision of North America with buoyant arc crust should coincide with observed deformation and accretion events.

Figure 3b shows inferred terrane locations before override: each active trench/arc system may include a subduction complex or exotic fragments. Using geological relationships in the present-day Cordillera[1], we can match most hypothesized terranes with actual ones. ANG terranes (red) now make up the interior of Alaska, in fault contact with the Angayucham and related ophiolites. Those studying Alaska have long inferred a southwest-dipping subduction[29].

Green terranes west of A1 represent the Franciscan subduction complex of present-day California. Two superterranes from earlier subduction had already loosely accreted to North America before archipelago override began: the IMS closest to the continent[4,5], and the GUE to the south[6], whereas the INS superterrane[4] probably provided the subduction nucleation for the MEZ arc.

To provide for independent validation, our calibration points for sinking rates were chosen at tectonic events that are sharply defined in time and space (A1–A5 in Table 1). Events B1–B5, which are interleaved with the A1–A5 events, represent widespread Cordilleran orogenic and accretion episodes, demonstrating explanatory power on a continental scale. Four stages of override are distinguished, as follows.

Stage 1 (see Fig. 3a, b) is the beginning of the override of the east-verging MEZ promontory. Deformation was initially localized to the Pacific Northwest, as predicted by our model. Incipient deformation of the hinterland generated molasse that flooded the continental platform about 157 Myr ago between 45 and 55° N (ref. 30). A flip in subduction direction at about 165 Myr ago[31] is recorded by the transition from proto-Franciscan formation (for example, the Red Ant formation[32], shown as orange terranes southwest of A1 in Fig. 3b) to Franciscan formation (green), marking an early subduction handover from MEZ to SF2.

Stage 2 (Figs 3c, d) is the time of margin-wide orogenies as North America collided with an increasingly wide swath of MEZ/SF. This caused the Sevier and Canadian Rocky Mountains orogenesis since around 125 Myr ago. Inboard parts of IMS were partly constructed on top of stable North American crust in southern California[33] and had largely collapsed by 110 Myr ago, increasingly shedding zircons onto stable North America[34], and vice versa; whereas IMS and the active Sierra Nevada arc shed zircons into the Franciscan trench[33] (SF2). Intrusion of Omenica magmatic belts successively eastward into northern IMS and adjacent displaced North American strata[8] (B1, about 124–90 Myr ago) can be attributed to prolonged override of the MEZ promontory.

Stage 3 (Fig. 3e, f) is when North America entered the Farallon hemisphere. As ANG collided obliquely, its terranes (red; now interior Alaska) were accreted along the Canadian margin. Override of A3

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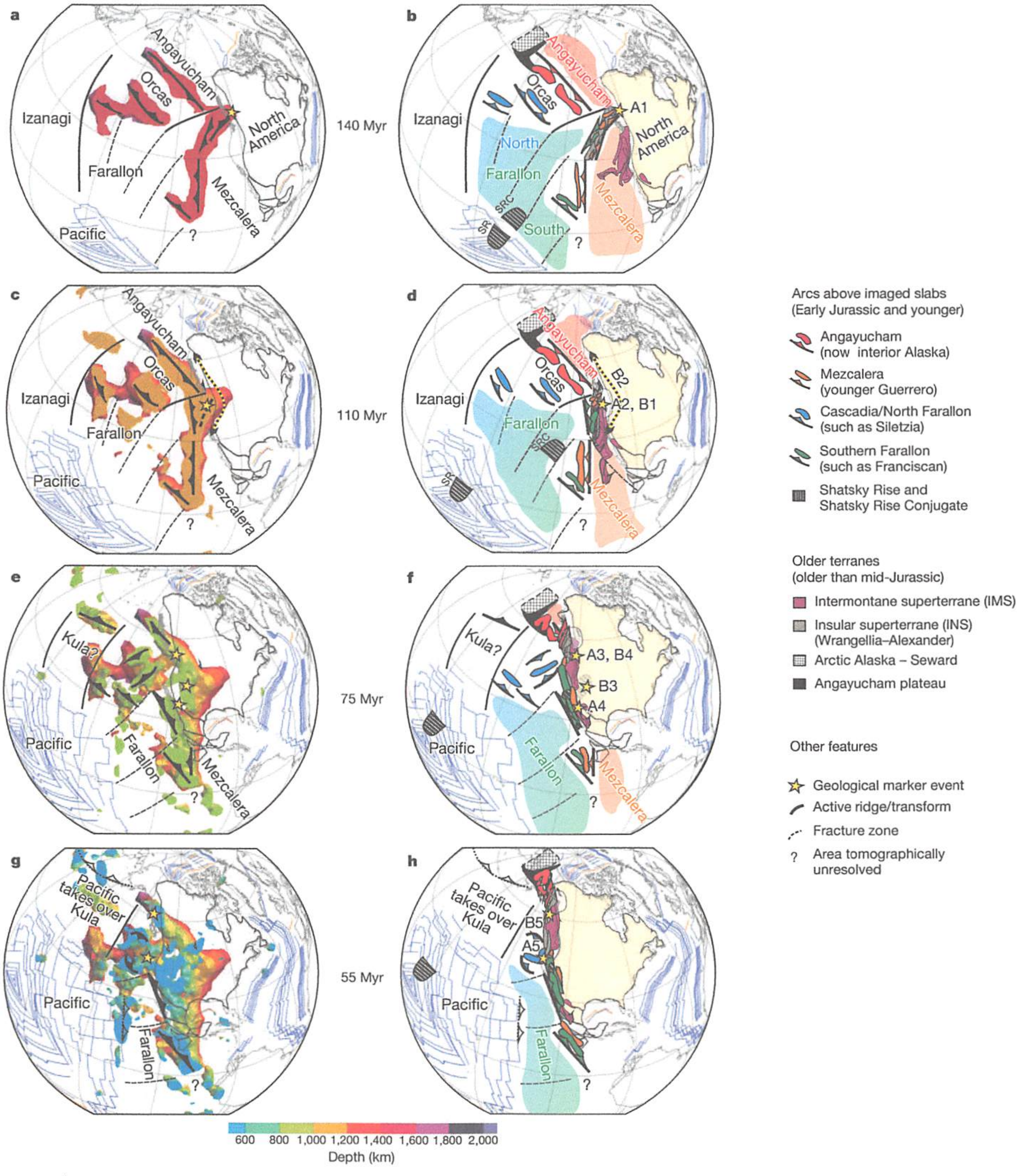

Figure 3 | Sequence of trench overrides and terrane accretions. The left column (**a**, **c**, **e**, **g**) shows time-depth slices at $t = 140$, 110, 75 and 55 Myr ago; the tomography model and plate reconstructions are rendered as in Fig. 1. Each slice shows only material that should have been deposited by that time, that is, slab at and below a depth of $v \times t$, where $v = 10\,\mathrm{mm\,yr^{-1}}$ is the assumed sinking rate. All slabs are coloured according to their current depths, but mentally their upper truncations should be migrated up to the surface, representing the inferred active arc locations at each time. The 140-Myr-ago slice renders slab below 1,400 km depth; the 110-Myr-ago slice renders slab below 1,100 km; the 75-Myr-ago slice below 750 km; and the 55-Myr-ago slice below 550 km. Blue lines are preserved seafloor isochrons. The associated maps in the right column (**b**, **d**, **f**, **h**) are interpretative cartoons showing the evolution of inferred trench and terrane geometries. Yellow stars mark the tectonic events of Table 1. SR, Shatsky Rise; SRC, Shatsky Rise Conjugate.

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Table 1 | Sequence of archipelago override

Event	Geometric/kinematic event description	Matched geological validation event	Reconstructed time, t (Myr ago)	Slab depth, d (km)	Slab sinking velocity, v (mm yr^{-1})
A1	Start override of MEZ promontory. Overridden segment is replaced by incipient South Farallon trench SF2.	Initiation of Rocky Mountain deformation, recorded by synorogenic clastic wedge (160–155 Myr ago). Initiation of Franciscan subduction complex/South Farallon (165–155 Myr ago).	146 ± 24	1,500 ± 100	10 ± 2
B1	Gradual override of MEZ promontory by North America (Pacific Northwest).	Omenica magmatic belts in Pacific Northwest (124–90 Myr ago).	-	-	-
A2	End override of MEZ promontory (shallowest point of slab wall).	-	111 ± 8	1,050 ± 50	9 ± 1
B2	Widening collision of North America margin with archipelago (MEZ/ANG/SF arcs).	Margin-wide strong deformation: Sevier and Canadian Rocky Mountains (since about 125 Myr ago).	-	-	-
A3	Override of ANG arc, followed by slab window.	Carmacks volcanic episode due to slab window (72–69 Myr ago).	74 ± 7	850 ± 50	12 ± 1
A4	South Farallon trench steps westward after accretion of Shatsky Rise Conjugate plateau.	Sonora volcanism due to slab window: Tarahumara ignimbrite province (85 ± 5 Myr ago).	88 ± 3	800 ± 50	9 ± 1
B3	Strong transpressive coupling of Farallon plate to superterranes as buoyant Shatsky Rise	Laramide orogeny, basement uplift more than 1,000 km inland (85–55 Myr ago).	-	-	-
B4	Conjugate subducts.	Northward shuffle of INS, IMS, and ANG terranes along margin (85–55 Myr ago).	-	-	-
A5	Override of CR arc by Pacific Northwest USA	Last terrane accretions: Siletzia, Pacific Rim (55–50 Myr ago).	55 ± 7	600 ± 30	12 ± 2
B5	Final override of westernmost ANG.	Explosive end of Coast Mountain arc volcanism (55–50 Myr ago).	-	-	-

Column 2 describes tectonic events in terms of geometrically predicted slab–margin interactions. Column 3 describes matching events from the land geological record. For well-localized events (A1–A5), we estimate slab depth d, time t since last subduction (margin override), and slab sinking rate v, from the tomographic and plate models. Calculations are explained in the Methods; for uncertainty analysis see the Supplementary Information. Geologically observed timing does not enter the calculations, since the role of the geological events is to validate the geometrically inferred results. Events B1–B5 represent additional, first-order tectonic episodes explained by the scenario of archipelago override (these are not localized enough spatiotemporally to estimate d, t and v).

was accompanied by a strong pulse of intermediate to basaltic volcanism, the Carmacks formation at around 72–69 Myr ago[35]. Such high-temperature, mainly primitive volcanism arises from juxtaposition of hot, sub-slab asthenosphere after a slab, broken through arc collision (Fig. 2b), has started to sink[36].

The South Farallon trench was migrating westward with North America, still building the Fransciscan formation. Around A4, slab geometry indicates an outboard step from SF2 to SF3. This coincides with a strong regional pulse of ignimbrite volcanism at 90 Myr ago (Tarahumara formation, up to 4 km thick and 400 km inland[37,38]) as the southern California/Sonora margin traverses the intermittent slab gap.

The location and timing of this trench step-back coincide almost perfectly with the inferred arrival of a buoyant oceanic Farallon plateau at the North America margin, the conjugate half of the Shatsky Rise (Fig. 3 includes its reconstruction by ref. 39). Plateau collision is a proposed mechanism[39,40] for choking subduction and causing the basement uplifts of the Laramide orogeny at around 85–55 Myr ago (B3). We suggest that the event explains another first-order observation of Cordilleran geology (B4): the INS/IMS and ANG terrane packages, but not Franciscan and GUE, were rapidly shuffled northward along the margin between 85 and 55 Myr ago, by many hundreds to over 2,000 km (ref. 41). The convergence vector of the Farallon plate did have a large northward component at the time[2], but terrane transport additionally requires strong coupling to the Farallon plate and decoupling from North America. A buoyant Farallon plateau, compressed against INS/IMS and unable to subduct, could have achieved such coupling until the trench re-established itself further west.

Stage 4 (Fig. 3g, h) is the end of archipelago override. North America overrides point A5 at 55 ± 7 Myr ago, in excellent agreement with last observed terrane accretions in the Pacific Northwest (Siletzia, Metchosin and Pacific Rim terranes at about 55–50 Myr ago[42–44]). The trench stepped west (clear upward truncation at A5) as the terranes accreted, converting intra-oceanic CR into today's continental Cascadia subduction. Also at about 55–50 Myr ago, ANG was terminally overridden (B5), accompanied by explosive volcanism as the Coast Mountain arc of British Columbia shut down.

By then, slab complexity in the upper mantle rivalled today's western Pacific—not surprising given the numerous forced reorganizations. The simple depth–age relationship suggested by Fig. 3 need not apply to flat-lying Cenozoic slabs[13] or to isolated deeper fragments like Kula or CR3, because all sinking estimates were calibrated on slab walls. We do not attempt to interpret upper-mantle structure and the Cenozoic land record here, but our archipelago model provides a new framework for doing so.

Better constraints on surface and mantle

Long-lived, stationary oceanic trenches explain two problematic observations, previously thought to be unconnected: the near-vertical geometries of the super-slabs under North America (without invoking exceptional mantle rheologies or *ad hoc* shifts in absolute reference frame), and the long series of arc terrane accretions during Cretaceous times[1] (not explained by the South American analogy).

An archipelago offshore Mesozoic North America had previously been suggested on the basis of land geology[7,8], but lacked the absolute spatial constraints provided by seismic tomography and our vertical sinking/terrane stations concept. Now-displaced terranes can be tied to their original, seismically imaged trench locations, but also to reconstructed continent locations, in an absolute reference frame. The hypothesis that continental collision with stationed terranes caused the various episodes of Cordilleran mountain building becomes testable.

Before 150 Myr ago, North America was clearly located too far east for MEZ/ANG to pass for continental trenches, even when longitudinal uncertainties of absolute reference frames[45] are factored in (Fig. 1 and Supplementary Fig. 3, and Supplementary Tables 1 and 2). The apparently 'wrong' geometry and locations of the vertical slab walls—under the hypothesis of subduction of the Farallon plate beneath North America—had been recognized[12,27,46,47] with two kinds of solutions suggested. A longitudinal shift of the global lithospheric shell relative to the lower mantle[12], specifically a Cretaceous westward excursion that tapered down as the Atlantic opened, could have held North America stationary above MEZ/ANG. Alternatively, upper-mantle slab, spread out laterally by a west-coast trench, must somehow have aggregated into steep piles when transitioning into the lower mantle. This requires lateral displacements by over 1,000 km of huge volumes of slab[27,46]. Some convection simulations have produced such behaviour[46,48], whereas others suggest essentially vertical sinking[47], as do newer observations[12,13,18].

We showed that, within observational uncertainty limits, predicted and observed geological events are consistent. This validates simple vertical sinking and seems to explain all North American observations,

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including accreted terranes, but is incompatible with the widely accepted continental Farallon trench since 175 Myr ago or before. The observed proportionality between slab depth and time since override (consistent sinking rates across all three slab walls) is not required for our argument, but rather increases confidence in its correctness.

Vertical slab sinking provides much tighter constraints on palaeogeographic reconstructions than arbitrarily movable slabs. This scenario follows the principle of parsimony, so that future investigations should start with it, and seek observations requiring a departure from it. The equivalence of hotspot and "slab wall" absolute reference frames, which is implied by vertical sinking, is of great interest because slabs reach back farther in time than hotspot tracks (200 Myr ago or more[12,49] versus about 130 Myr ago[21,22]), and they constrain absolute palaeo-longitude, which palaeomagnetic data alone cannot[50]. However, to quantitatively realize a global subduction reference frame[12], it will be necessary to re-examine whether trenches commonly assumed to have been continental were not actually intra-oceanic.

METHODS SUMMARY

We postulate that subduction into all slab walls imaged tomographically beneath North America[13] originated before the arrival of North America's western margin. Hence we must demonstrate sufficiently old slab ages, and cessation or flipping of subduction when the continent overrode the slabs. Plate reconstructions predict the timing of margin arrival above a slab, but only if slab[13] and plate reconstructions[12,21,22,50–52] can be linked to the same absolute reference frame. Hence override predictions are correct to the extent that slab walls sank vertically, meaning that their x–y locations since subduction are unchanged in a linked hotspot reference frame. Uncertainty is best quantified from slab wall geometry itself: deviation from vertical sinking probably did not exceed a wall's half-width (200–300 km), else such steep geometries could not have built up over a long time.

Uncertainties about absolute locations of North America's palaeo-margin arise from imperfections in plate reconstructions. Owing to terrane accretions and removals, there is also uncertainty about the shape and westward extent of North America's margin, compared to its present-day outlines. We discuss individual uncertainties in the Supplementary Information, and propagate them into cumulative uncertainties for the times at which North America's palaeo-margin overrode selected points A1–A5 on the palaeo-trenches. With relative uncertainties of only 10–15% (Table 1 and Supplementary Tables 1 and 2), this yields the old (Jura–Cretaceous) slab ages required to support intra-oceanic subduction.

Spatiotemporal predictions of trench override are verified by terrane observations: override should coincide with observable collision events, because buoyant island arcs or plateaus are overridden. Uncertainties on terrane observations are difficult to quantify, but particularly characteristic events (A1–A5) can nonetheless be singled out and used successfully for validation (Table 1). Clear upward truncations of all slab walls offer direct observational evidence for continental override of oceanic trenches, and are used to calculate slab-wall sinking rates.

Full Methods and any associated references are available in the online version of the paper.

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Supplementary Information is available in the online version of the paper.

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Author Contributions K.S. generated the tomographic model, and integrated it with quantitative plate tectonic reconstructions in GPlates. M.G.M. provided the geological background and made the terrane maps of Fig. 3. Both authors contributed equally to developing the tectonic arguments and to the writing.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to K.S. (sigloch@geophysik.uni-muenchen.de) or M.G.M. (Mitch.Mihalynuk@gov.bc.ca).

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METHODS

The MEZ/ANG slab walls have been among the most robust features in global-scale body-wave tomography, starting with the work of Grand[9–13,28]. The deep end of the CR slab was already visible in some of the earlier studies. Its continuous upward connection to present-day Cascadia subduction was pointed out by ref. 15, hence its identification as a Farallon slab. The model on which we base our discussion here[13] is an inversion of P-wave observations recorded by North American broadband stations, using a cutting-edge waveform inversion technique (multi-frequency tomography) on a global, adaptive grid. Method discussion and formal resolution tests are presented in ref. 13. The higher resolution compared to global tomography models is largely due to densely spaced stations from the USArray experiment in the western half of the US, and waveforms recorded 2005–2008, which were not included in any of the above global models. Our calibration points for sinking rate, especially A3–A5, lie within the mantle subvolume that considerably benefits from resolution improvements afforded by the new USArray data.

We postulate that subduction into all slab walls imaged tomographically beneath North America[13] originated before the arrival of North America's western margin. Hence we must demonstrate sufficiently old slab ages, and cessation or flipping of subduction when the continent overrode the slabs. Plate reconstructions predict the timing of margin arrival above a slab, but only if slab and plate reconstructions[12,21,22,50–52] can be linked to the same absolute reference frame. (Technically we accomplish this with the free community palaeo-geographic information system GPlates[23,24] and a compilation of digitally published reference frames[45].) Hence override predictions are correct to the extent that slab walls sank vertically, meaning that their x–y locations since subduction are unchanged in a linked hotspot reference frame. Uncertainty is best quantified from slab wall geometry itself: deviation from vertical sinking probably did not exceed a wall's half-width (200–300 km), else such steep geometries could not have built up over a long time.

Uncertainties about absolute locations of North America's palaeo-margin arise from imperfections in plate reconstructions. Owing to terrane accretions and removals, there is also uncertainty about the shape and westward extent of North America's margin, compared to its present-day outlines. We discuss individual uncertainties in the Supplementary Information, and propagate them into cumulative uncertainties for the times at which North America's palaeo-margin overrode selected points A1–A5 on the palaeo-trenches. With relative uncertainties of only 10–15% (Table 1 and Supplementary Tables 1 and 2), this yields the old (Jura–Cretaceous) slab ages required to support intra-oceanic subduction.

Spatiotemporal predictions of trench override are verified by terrane observations as follows. Override should coincide with observable collision events, because buoyant island arcs or plateaus are overridden. Uncertainties on terrane observations are difficult to quantify, but particularly characteristic events (A1–A5) can nonetheless be singled out and used successfully for validation (Table 1). Sinking-rate calculations provide an additional plausibility check. Consistent results of 9–12 mm yr^{-1} (±1–2 mm yr^{-1}) across all three slab walls show that this type of feature seems to sink rather predictably and evenly. If this is the case, then conversely the override prediction times that lead to the rate estimates should be adequate.

Sinking at about 10 mm yr^{-1} is considered a lower-mantle sinking rate, but we obtain it as an average over both upper and lower mantle. This is explicable if a wall were to have sunk in steady state: upon subduction of its youngest end (Fig. 2b), its lower part would already have entered the viscous lower mantle and would have been setting the speed limit from below, which would have acted on the entire pile. Such a wall, widened to 4–6 times the lithospheric thickness (400–600 km), and sinking at about 10 mm yr^{-1}, generates the same material throughput as the typical 40–60 mm yr^{-1} of unbuckled plate convergence in the uppermost mantle[16,20]—a plausibility check that confirms the continuity of upper and lower mantle fluxes.

Sinking rates are obtained by dividing the imaged depth of a wall's shallowest end (depth reached since the end of subduction) by predicted time since the trench override. Besides timing uncertainty, a spatial uncertainty about the slab's true depth enters, as discussed quantitatively in Supplementary Fig. 2. These uncertainties are comparatively small, because upward truncations of the slab walls are sharply imaged. This is also a striking visual feature (see, for example, Fig. 3g or Supplementary Fig. 2): along their lengths, MEZ and ANG show abrupt upward truncations in red to orange, yellow and green depth levels. This provides direct observational evidence for westward subduction—after trench override, there was no slab left to subduct. In contrast, the less-complete upward truncation of eastward-dipping CR around A5 (cyan colour level, a more localized slab window) indicates 'only' a larger terrane accretion event and trench step-back when the margin transitioned from intra-oceanic to Andean-style. Upward truncations shallow to the west (A1 at red level, A2 at yellow level, A3/A4 at green level, and A5 at cyan level), reflecting more and more recent ages for termination of subduction.

In summary, the observational uncertainties that we discuss in the Supplementary Information are:

(1) Uncertainties in plate reconstructions at the surface. When exactly did the North American palaeo-margin overlie a given point in the reference frame, for example, A1-A5? This includes relative reconstruction uncertainties (essentially ambiguities about the Atlantic Ocean opening; they are small, and neglected in our calculations); uncertainties about absolute reference frame (these are considerable; we attempt to quantify them by comparing different reference frames[12,21,22,45,50–52] (Supplementary Fig. 3); and uncertainties about the true westward extent of the palaeo-margin over time. The latter uncertainty is most difficult to quantify, since it requires knowledge about accreted terrane locations, which shifted over time. Our best guess of the uncertain area's extent is hatched in Fig. 1a and b and Supplementary Fig. 3a and b. Margin uncertainty is the biggest contributor to reconstruction uncertainties (typically 6–7 Myr), except for the oldest point A1, where absolute reference frame uncertainty dominates (Supplementary Table 2).

(2) Uncertainties in palaeo-trench locations, relative to the slab. Were trench points A1–A5 centred on the imaged slab walls, systematically offset to one side, or oscillating? We assume that the trenches ran centred, for lack of evidence to the contrary. A constant offset would hardly change the calculations, producing a strong correlation with margin uncertainty rather than independent uncertainties. Periodic trench advance and retreat—as buckling folds are being laid down—cannot be excluded, but we are unaware of observational evidence. Unless these oscillations significantly exceeded the half-width of the slab wall of 200–300 km (unlikely, given the tall slab piles), they would not dominate over margin uncertainty.

(3) Uncertainties about present-day slab depth (pertinent only to sinking-rate estimates). Evaluation of tomographic blur yields significantly smaller relative uncertainties than reconstruction errors (Supplementary Table 1). The two types of relative errors enter symmetrically into cumulative uncertainty on sinking rate.

Regarding our hypothesis of intra-oceanic trenches, the most important, qualitative assessment of uncertainty is that all the plate reconstructions considered[21,22,45,50–52] (with one exception[12] discussed below) agree that two ocean basins should have existed between North America and the MEZ/ANG slabs before 140 Myr ago (Fig. 1a and Supplementary Fig. 3a). These oceans were considerably wider than the uncertainty in margin extent, implying intra-oceanic subduction origins for all imaged slab walls, provided they are older than 140 Myr. That this is the case is shown by good agreement between predicted and geologically observed collision events (within the moderate error bars of Table 1). An extrapolation of sinking rates of about 10 mm yr^{-1} to the lower ends of the slab walls at over 1,800 km depth implies that subduction originated at least 180 Myr ago.

The one reference frame[12] that does not predict wide ANG/MEZ ocean basins in the late Jurassic/early Cretaceous was explicitly designed to minimize their extents, by imposing a constraint that keeps North America's western margin stationary above the MEZ/ANG slabs (that is, an Andean-style margin is enforced a priori; SUB on Supplementary Fig. 3b). This is accomplished by introducing an additional degree of freedom, an *ad hoc*, otherwise non-observable, westward shift of the lithospheric shell relative to the lower mantle. In solving for this longitudinal shift, the method considers a global slab inventory, but for the times discussed here, the influence of the MEZ/ANG slabs dominates. Hence, this reference frame does not lend itself to evaluating the existence of the ANG/MEZ oceans.

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