

Subduction dynamics and the origin of Andean orogeny and the Bolivian orocline

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The building of the Andes results from the subduction of the oceanic Nazca plate underneath the South American continent^{1,2}. However, how and why the Andes and their curvature, the Bolivian orocline, formed in the Cenozoic era (65.5 million years (Myr) ago to present), despite subduction continuing since the Mesozoic era³ (251.0–65.5 Myr ago), is still unknown. Three-dimensional numerical subduction models demonstrate that variations in slab thickness, arising from the Nazca plate's age at the trench, produce a cordilleran morphology consistent with that observed^{1,2}. The age-dependent sinking of the slab in the mantle drives traction towards the trench at the base of the upper plate, causing it to thicken. Thus, subducting older Nazca plate below the Central Andes can explain the locally thickened crust and higher elevations. Here we demonstrate that resultant thickening of the South American plate modifies both shear force gradients and migration rates along the trench to produce a concave margin that matches the Bolivian orocline. Additionally, the varying forcing along the margin allows stress belts to form in the upper-plate interior, explaining the widening of the Central Andes and the different tectonic styles found on their margins, the Eastern and Western Cordilleras². The rise of the Central Andes and orocline formation are directly related to the local increase of Nazca plate age and an age distribution along the margin similar to that found today; the onset of these conditions only occurred in the Eocene epoch⁴. This may explain the enigmatic delay of the Andean orogeny, that is, the formation of the modern Andes.

Several outstanding issues concerning the Andean orogeny currently remain unaddressed. Despite subduction and Western Cordillera tectonics beginning as early as the Cretaceous period³, ~140 Myr ago, widening to the Eastern Cordillera and Bolivian orocline formation did not start until the Eocene⁵, ~45 Myr ago. The plateau region sandwiched between the Cordilleras remained undeformed until the Miocene epoch⁶, ~10 Myr ago, when the whole Central Andes rose to reach modern elevations. Yet, it remains unexplained why the Andes and the orocline formed only in the Cenozoic, why the deformation then leaped 500 km into the plate's interior to the Eastern Cordillera, and why and how it affected the plateau region much later. Furthermore, an explanation is still lacking for the curvature of the Bolivian orocline, one of the few concave convergent margins on Earth.

The Andean chain displays distinct topographic features with a strong symmetry around the Central Andes^{7,8} (Fig. 1a). This segment of the belt is the widest, ~600–800 km, and hosts the highest elevations, ~5 km (Fig. 1b). Northwards and southwards, the altitude and width of the chain decrease smoothly. The Central Andes comprise the Western and the Eastern Cordilleras, both of similar elevation, separated by the Altiplano-Puna plateau (Fig. 1b, c). Crustal thicknesses of 60–80 km are measured in this region, whereas values of 40 km are found elsewhere⁹. The Central Andes corresponds to the largest curvature of the Bolivian orocline, marking a bend in the mountain chain.

The symmetry along the Andes correlates remarkably with the symmetric features of the Nazca plate^{7,8}. At the centre of this oceanic

plate, below the Central Andes, the lithosphere is oldest (~50 Myr), thickest, and most negatively buoyant, and progressively becomes younger towards the north and south, where mid-ocean ridges are subducting (Fig. 1a, b). Below the Central Andes, the dip of the Nazca slab shallows to ~50°. Two segments of very shallow slab border the Central Andes, but at depths greater than 200 km the slab bends again to dips of 70–80° (refs 4, 10). Faster subduction hinge migration occurs along the limbs of the continent¹¹. When extrapolated to a common time interval, geodetic and palaeomagnetic data on

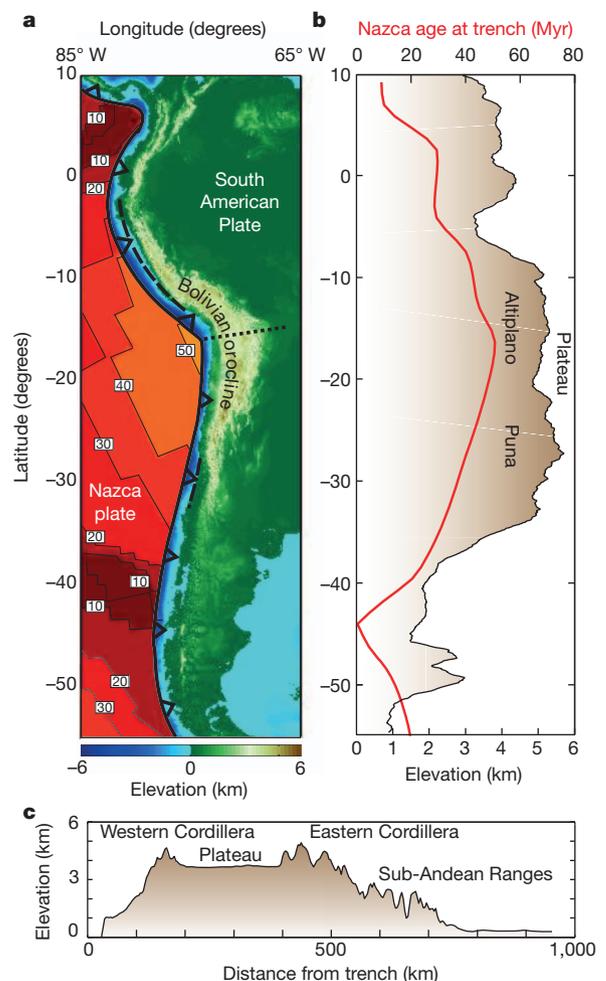


Figure 1 | The Andes and South American subduction. **a**, Andes topography (digital elevation model GTOPO30) and Nazca oceanic plate age⁴. The trench is indicated by thick line with triangles (dashed line for flat slab segments¹⁰). Dotted line, profile in **c**. **b**, Maximum along-margin Andes topography (black line with brown shading), and Nazca plate age at trench (red line) in Myr. **c**, Topographic profile across Central Andes. See **a** for location.

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both flanks of the Bolivian orocline are similar, showing that the present-day margin motions and deformations are representative of the long-term growth and bending of the Andes^{5,12}.

The strong correlation between topography and extent of the Andean Cordillera with corresponding variations in the Nazca slab has long suggested a causal relationship with the underlying subduction dynamics^{7,8}. Several models have investigated how processes related to subduction can shape the Andes. Shear stress at the plates' interface¹³, possibly due to friction^{14–16}, sub-lithospheric mantle flow^{17,18}, or a combination of the two¹⁹, can reproduce the topography of the chain. Alternatively, relative plate convergence²⁰, lithospheric weakening¹⁵ and climate-driven surface processes^{14,21} have been invoked to explain the Andean evolution. However, the models proposed are unable to describe the evolution of the Andes and the Bolivian orocline as emerging features of a dynamic subduction system.

A regional-scale three-dimensional geodynamic model can help address these questions, by testing the relative contributions of the forces driving the motions and deformations around the convergent margin. Here we use a numerical model of subduction²², in which an overriding plate is coupled to a 6,000-km-wide plate subducting into the mantle under the pull of its own negative buoyancy, and plate motions and tectonic stresses are emergent quantities (Supplementary Information). We find that consideration of the third dimension is the key to understanding the role of strong lateral stress gradients

due to the heterogeneities in the subducting Nazca plate age and the South American plate thickness, along the convergent margin. In the downgoing lithosphere, age-dependent thickness influences the buoyancy, the largest driving force of subduction, and strength of the plate, controlling the dips, whereas in the upper plate, thickness affects the strength as well as the area of the margin interface, and thereby the integrated shear force locally resists subduction. Therefore, the subducting plate is modelled with either uniform thickness, or with a central thickened region, corresponding to the oldest oceanic lithosphere in the Nazca plate. Similarly, upper-plate model thickness is either uniform (40 km), or includes a 60–80 km thickened central portion, similar to the estimated crustal thicknesses along the South American margin⁹.

Results indicate, as expected, that the age of the downgoing lithosphere has a first-order control on the velocity of subducting plate and on the topography of the overriding plate. The larger negative buoyancy force of an older and thicker subducted slab drives faster convergence. Stress at convergent plate margins directly correlates to the slab vertical sinking rate, modulated by the dependence of buoyancy on age. This is because faster sinking drives more vigorous flow in the mantle wedge, increasing traction at the base of the overriding plate and causing it to thicken. In the models, this is indicated by vertical stresses and is a measure of the excess crust required to balance the stress, which is directly reflected in increased topography.

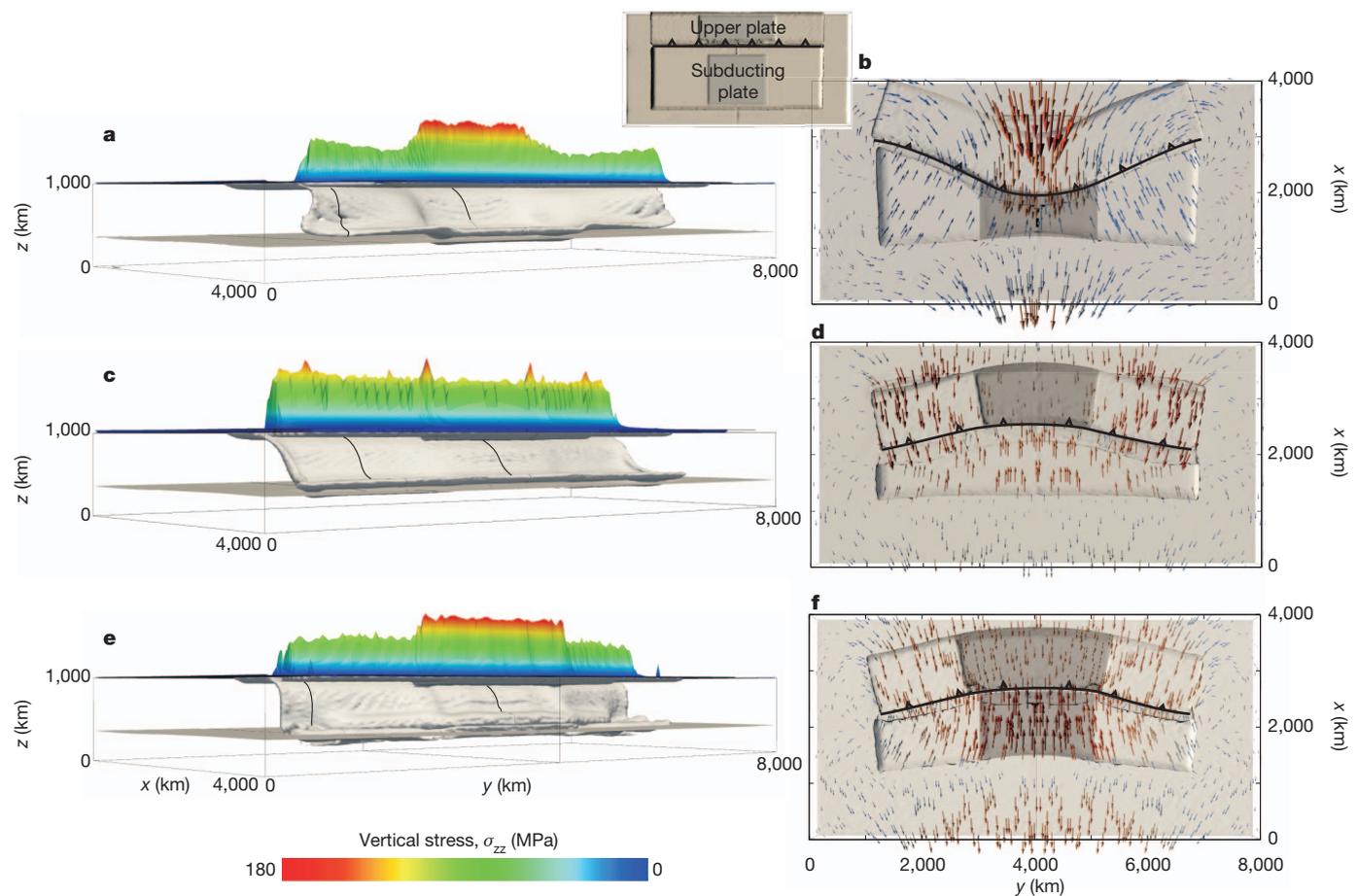


Figure 2 | Subduction models with slab morphologies, vertical stresses and velocities, after 2,000 km of subduction. Left column, three-dimensional view of the viscosity field contour (grey surface) and the vertical stress in the upper plate above the trench (coloured surface above the model box). The model space is a Cartesian box of 4,000 × 8,000 × 1,000 km respectively in length (x), width (y) and height (z). Shown are the contour surface for the lower mantle's top (at $z = 340$ km), the subducting slab (between depths of 1,000 and 340 km) and plates at the surface (dark grey, $z = 1,000$ km). The black line at

$z = 1,000$ km is the top surface of the model. Right column, two-dimensional plan view of the surface, showing viscosity field contour (grey surface) and velocity field (arrows). **a, b**, Model with subducting-plate thickness heterogeneity. **c, d**, Model with upper-plate thickness heterogeneity. **e, f**, Model with thickness heterogeneities in both subducting and upper plates. Solid line with triangles, trench trace; dark shaded area, the thicker portion of the plates. Velocity is 0 to 8 cm yr⁻¹ (blue to red). Top inset, initial configuration for **e, f**. Plates are initially straight and change morphology during subduction.

First, we tested the role that the older, thicker segment in the downgoing lithosphere has in subduction. This model includes a simplified version of the present-day Nazca plate age gradient at the trench, and generates several similarities with the Andean topography and Nazca subducted plate morphology along the margin. In the model's uniformly thick upper plate, vertical stresses reach a maximum of ~ 150 MPa (Fig. 2a), which are compensated by $\sim 5,500$ m of constant density continental crust (2.75 kg m^{-3}), and are thus compatible with Central Andean elevations. Also, vertical stresses decrease northwards and southwards, comparable to the observed elevation drop. Dip of the Nazca plate below the Central Andes, where oceanic lithosphere is older, is consistent with our model, as well as the steeper deep slab outwards, where the Nazca plate is younger. No flat slab occurs in our models. It is likely that other mechanisms become relevant at smaller scales²³, although these cannot hamper the deeper sinking of the slab. Faster subduction where the integrated slab pull is larger also promotes faster rollback, and the trench eventually forms a convex margin (Fig. 2b), opposite to the curvature of the Bolivian orocline.

The second model had a uniform subducting plate but included variation of the upper-plate thickness. In contrast to the first model, it did not reproduce north–south variation of vertical stress above the trench, but showed constant topography instead (Fig. 2c). This is related to constant velocities and slab dips (Fig. 2d), resulting from constant slab buoyancy and strength. In this model, upper-plate thickness variation along the trench reproduces realistic shear force gradients along the South American margin, increasing by a factor of ~ 2 below the Central Andes¹⁴ with respect to values further out. These gradients cause rollback to be slowest in the central, thickest part, ultimately causing bending in a concave morphology (Fig. 2d). This process might explain the long-term bending of the Bolivian orocline around the thicker Central Andean lithosphere.

When these heterogeneities are combined in a single model (Fig. 2e, f), the dynamics of the Nazca plate, the Andean topography and Bolivian orocline can all be reconciled. Results demonstrate that symmetric changes in the age of the subducting plate, older and thicker in its centre, cause symmetric changes in plate motions, dips and vertical stresses, reflected as a topographic high in the Central Andes, decreasing symmetrically outwards. In turn, the symmetric variations in thickness of the upper plate overcomes its natural tendency to bend into a convex margin²⁴, and instead forms a concave margin like the Bolivian orocline (Fig. 2e, f).

These different mechanisms, related to the subduction dynamics, can offer an explanation for the complexities in the Central Andean tectonics. Isostatic equilibrium of a uniform felsic 70–80 km crust⁹, mostly thickened with negligible thrusting²⁵, can account for the Western Cordillera elevations². Similar heights are explained by isostatic compensation of modelled vertical stresses above the trench. Instead, in the Eastern Cordillera, large crustal thickness is achieved by shortening along deep-seated thrusts²⁵, thus requiring stress propagation far into the continent's interior. Figure 3 shows intraplate stress and dynamic pressure in the upper plate for the model that includes both heterogeneities. Two zones of high shear stress develop at an angle to the trench (Fig. 3a), above the thickest segment of the downgoing plate. Along these belts the large horizontal stresses accommodate the different forcing at the margin. The distinct spatial localization of these mechanisms leaves an area in between where stress is negligible (Fig. 3c). This may explain the different regimes underlying the Western and the Eastern Cordilleras and their morphology, as well as the lack of deformation in the plateau during the early stages of Central Andes evolution. Additionally, the pressure gradient towards the centre of the upper plate might drive orogeny-parallel crustal flow towards the plateau²⁶.

Further deformation only occurred subsequently (post-Oligocene), migrating to the plateau and the outer sub-Andean ranges²⁷. The results from three models where the thickness of the upper plate was uniform at 40, 60 or 80 km, show that thicker upper plates are stronger and

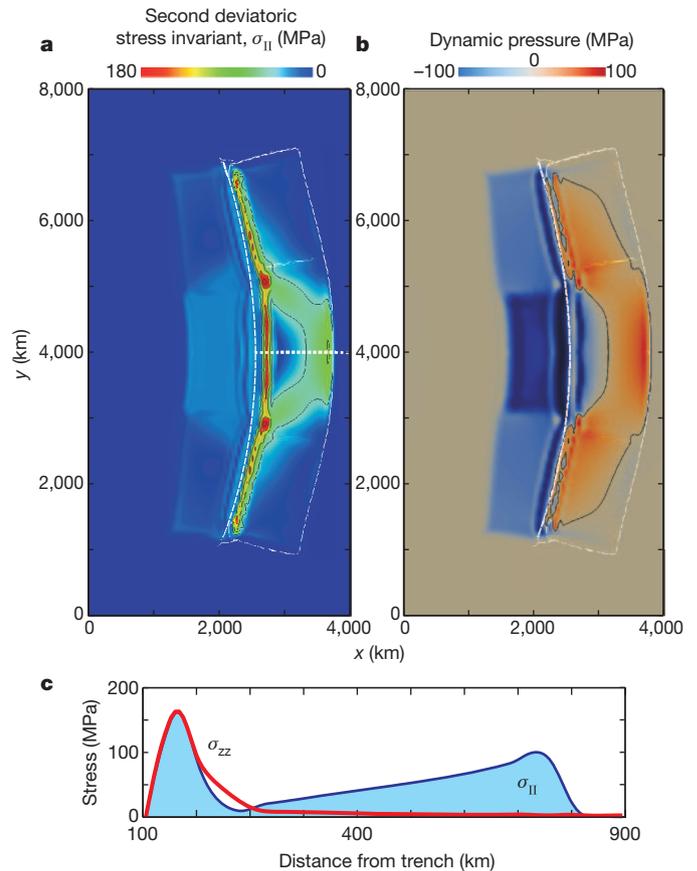


Figure 3 | Surface stress and pressure from the model with heterogeneities in both plates. This model shown in Fig. 2e, f, the upper plate is outlined in white. **a**, Second deviatoric stress invariant, σ_{II} . High stress above the trench and across the upper plate isolates a low-stress area. **b**, Dynamic pressure. Negative pressure occurs above the denser subducting plate segment. Black line, contour of zero pressure. **c**, Upper-plate stress, cross-section. Large vertical stress (σ_{zz} , red line) above the trench indicates thickening; high stress invariant (σ_{II} , blue line with shading) in the plate interiors and zero vertical stress indicates horizontal major stress. Profile location, dashed line in **a**.

compression propagates further into the plate's interior (Fig. 4a), which is required for outward orogen growth. Compression in the plateau is accommodated by thrust tectonics in the Bolivian Altiplano⁶, as opposed to pure-shear thickening in the Argentinean Puna⁶, achieved by diffuse faulting. In the Puna, the thickened lithosphere has eventually delaminated²⁸. In the models, we found that the peak differential stress deepens with the thickness of the modelled upper plate (Fig. 4b). Thus, we argue that similar stress localization at subcrustal depths might have triggered the delamination of the South American lithosphere. Stress focusing occurs when the upper-plate model thickens uniformly, but this might not be the case if plastic deformation continuously accommodates compression. This possibly explains why the lithosphere has only delaminated under some parts of the plateau⁹, even if it has similarly thickened and become unstable throughout.

Our models suggest that such diverse evolution can be reconciled with the boundary conditions that the Nazca slab buoyancy imposed on the South American continent. So the age of the subducted lithosphere going back in time might provide a first-order estimate of the driving forces during the Cenozoic, which could be verified against the timing of the Andean orogeny. The growth of both Cordilleras above the trench requires an increase in the age of the subducting plate, which would also drive a surge in the convergence. In contrast, the widening of the central part of the orogen and the bending of the orocline are both a response to the age gradients along the trench, leading to heterogeneous thickening of the upper plate. The increase of subducting plate age and the strong along-trench age gradients are

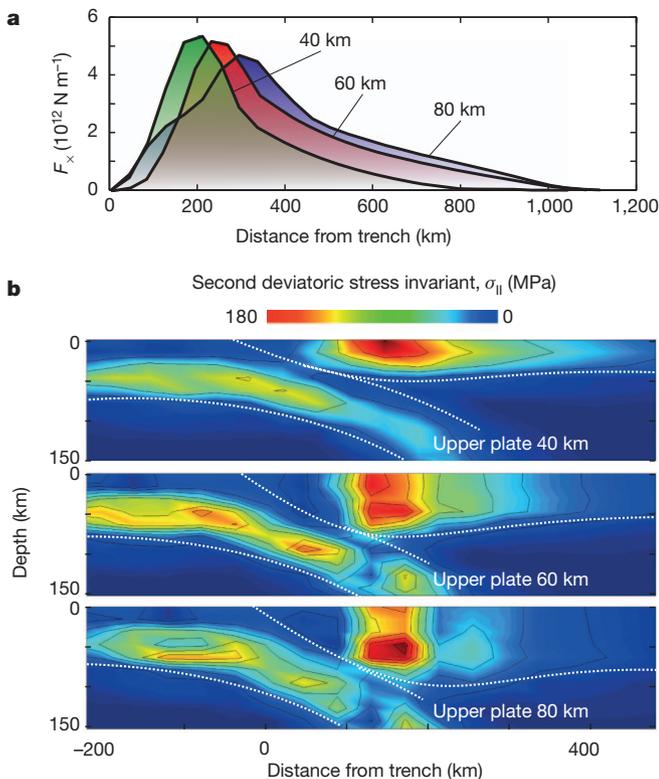


Figure 4 | Effects of upper-plate thickening. **a**, Integrated horizontal compressive force, F_x , propagated from trench in the upper plate. Models shown have overriding plates 40, 60 and 80 km thick. Compression propagates farther from trench with thicker, stiffer plates. **b**, Cross-section of the second deviatoric stress invariant. Profile location, dashed line in Fig. 3a.

conditions that might not occur at the same time, nor might they correlate, thus it is a natural (not exceptional) consequence that orogen growth occurred long after subduction had started.

Reconstructions of the Nazca plate age⁴ for the past 60 Myr (Supplementary Data) show that a strong, along-trench age gradient formed $\sim 45\text{--}40$ Myr ago, between 30° and 45° S (ref. 4), where older subducting plate entered the trench. The increased driving force can explain the fast convergence during this period^{4,20} and the inception of Eastern Cordillera tectonics²⁷. The present-day age gradient was not established until ~ 20 Myr ago⁴, when the Nazca plate migrated to its present-day location. This positioned ~ 70 -Myr-old lithosphere offshore from South America, which then became the oldest lithosphere subducted under the Central Andes since the early Cenozoic. This accounts for the second surge in the convergence rate^{4,20} as well as the local growth of the topography, above the northern and southern average elevation²⁷. As prescribed by our models, the timing of crustal growth matches the two major phases of oroclinal bending⁵. The progressive regional reduction in the age of the subducting Nazca plate since 15 Myr ago explains the decline of convergence rates to present-day values. The current convergence velocity varies little along the South American trench, reaching a maximum further south than the Central Andes²⁹, at $35\text{--}40^\circ$ S. This is possibly due to the increased pull of the deeper slab at these latitudes, where older, denser lithosphere has subducted before 25 Myr ago. Therefore, variations in the dominant plate driving force, slab pull, that naturally arise from heterogeneities in the seafloor age of oceanic plates, are linked to intervals of intense tectonic activity and quiescence, and to the corresponding time-history of convergent motions.

Heterogeneities in the downgoing and upper plates are features commonly found along all convergent margins. Thus, their controls on Andean-type chains, plate margin morphologies and continental deformation must have a global relevance.

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