The Andean cordillera was constructed during compressive tectonic events, whose causes and controls remain unclear. Exploring a possible link to plate convergence has been impeded by the coarse temporal resolution of existing plate kinematic models. Here we show that the Neogene evolution of the Andean margin is primarily related to changes in convergence as observed in new high-resolution plate reconstructions. Building on a compilation of plate finite rotations spanning the last 30 million years and using noise-mitigation techniques, we predict several short-term convergence changes that were unresolved in previous models. These changes are related to main tectono-magmatic events and require forces that are compatible with a range of geodynamic processes. These results allow to revise models of ongoing subduction orogeny at its type locality, emphasizing the role of upper plate deformation in the balance between kinematic energy associated with plate motion and gravitational potential energy stored in orogenic crustal roots.
The Andean Cordillera, an archetype of subduction-related mountain belts, is the result of hundred million years of convergence between various oceanic plates and the western margin of South America. This process left a marked along-strike segmentation of the continental margin. Segmentation is particularly obvious when considering variable amounts of Neogene crustal shortening, which ranges from more than 300 km at 20°S to less than 40 km at 40°S. Shortening has traditionally been related to the episodic development of compressional tectonic events that can be broadly recognized in the geological evolution of volcano-sedimentary basins, magmatic arcs and fault systems. However, the geodynamic mechanism explaining the occurrence of these compressional events as well as the causes for the along-strike variability of the associated crustal shortening remain controversial.

This mechanism should consider the dynamic coupling between both converging plates at the subduction zone, connecting compressional tectonic events with changes in plate motion. Such a relationship has been suggested, for instance, to explain an increase in tectono-magmatic activity along with changes in the tectonic style following an acceleration of convergence. Such a relationship has been suggested, for instance, to explain an increase in tectono-magmatic activity along with changes in the tectonic style following an acceleration of convergence. This event is related to dramatic changes in shortening rates, magmatism and surface uplift along the entire western margin of South America. However, large uncertainties in Neogene convergence history derived from available plate kinematic reconstructions have hampered establishment of a clear temporal link between changes in plate convergence and the tectono-magmatic evolution of the continental margin. As a consequence, some authors favor a direct control of upper plate deformation on convergence, while others observe no relationship between these two processes.

Temporal variations of Nazca-South America convergence can be reconstructed by combining finite rotations for the relative spreading motions across mid-oceanic ridges encompassed in the plate circuit Nazca-Pacific-Antarctica-Nubia-South America. Available kinematic reconstructions have featured a temporal resolution of 5–10 Myr. Recently, there has been progress in mapping Neogene spreading-motion variations at finer temporal resolution.

In this work we use a compilation of recently published finite plate rotations and statistical tools to mitigate the emergence of noise-related kinematic artifacts that appear at high temporal resolution, to obtain a reliable, high-resolution reconstruction of the Nazca-South America convergence during the Neogene.
An alternative study\textsuperscript{14}, which avoids passing through Nubia by using data collected in and around the Weddell Sea, yields kinematics that are in line with those of SG12. The spatial view provided by Fig. 1 is complemented with the temporal variability of convergence rate and azimuth depicted in Fig. 2. From these two figures, we note a first-order coincidence between our results and those of SG12 at the scale of \(~5\) Myr, like the maximum convergence rate after the birth of the Nazca plate in the Latest Oligocene and its subsequent decrease during the Neogene. However, SG12 imaged this deceleration as a gradual process under relatively fixed azimuth, whereas our model shows some large and rapid \((\sim 2\) Myr) changes in the rate and azimuth of convergence. Incorporating the Oligocene to Middle Miocene relative motion between East and West Antarctica\textsuperscript{40,41} into our reconstruction (Fig. 2) does not alter the temporal pattern of kinematic variations illustrated by our model, nor its main differences with SG12.

At the 68\% confidence level (one standard deviation with respect to the average) in Fig. 2, we note statistically significant differences in the uncertainty ranges of SG12 and ours, mostly during the time interval between \((15\) and \(5\) Ma), for which differences are also recognized at the more conservative 95\% confidence level (two standard deviations). Therefore, we will concentrate our further analyses in the Middle to Late Miocene evolution of convergence. After \((20\)–\(17\) Ma), SG12 shows a steady decreases of convergence rate at intervals of \(~5\) Myr from a peak of 15 cm/yr to a value of 10 cm/yr at 5 Ma. In contrast, our model predicts that the same magnitude of convergence slowdown occurs in a much shorter period between ca. 15 Ma and 12 Ma. The most relevant feature revealed by our model and the main difference with SG12 is a very rapid convergence acceleration between \((11\) and \(9\) Ma) reaching a peak of \(~14\) cm/yr all along the entire Andean margin. At 9 Ma our model predicts a decrease of convergence rate to a value around 12 cm/yr that remains relatively constant until 7 Ma when a sudden deceleration to a rate of 9 cm/yr took place. This is accompanied by a notable reduction in the azimuth of convergence from N83°E to N70°E. This value is nearly 10° lower than predicted by SG12, although our convergence rate is very similar to SG12 for the last 5 Myr. Our present-day convergence azimuth lies at the lower bound of GPS-based estimates, whereas our predicted rate is 30–50\% larger than current geodetic estimates. This important difference might be related to the megathrust seismic cycle, but this topic is beyond the scope of our present study.

In order to understand the source of differences between our kinematic plate model and SG12 it is important to note that these previous authors utilized a selection of Nazca/Antarctica finite rotations from another study\textsuperscript{42} to constrain motions of that part of the Nazca/South America plate circuit. This original study\textsuperscript{42} used mapped magnetic lines across the Chile Ridge\textsuperscript{43} to infer finite rotations of Nazca relative to Antarctica at chron 2 A \((\sim 3.5\) Ma), 3 \((\sim 4.9\) Ma) and 5 A \((\sim 12\) Ma). In addition to these,
the authors (i) interpolated finite rotations at chron 2 A and 3 to obtain a rotation for ~4 Ma, (ii) interpolated rotations at chron 3 and 5 A to obtain a rotation at ~11, and (iii) extrapolated chron 5 A to ~16 Ma (see Table 4 in ref. 42). From these original and extrapolated finite rotations at chron 3 (~4.9 Ma), the interpolated one at ~11 Ma, and the extrapolated one at ~16 Ma (see Supplementary Data in SG12). This effectively means that steadiness of Nazca/Antarctica motion is enforced by SG12 between ~16 and ~11 Ma, although the actual data can constrain motion only back to ~12 Ma. We believe this is the main reason for the difference between our reconstruction and SG12 between ~16 and ~11 Ma, although the actual data can constrain motion only back to ~12 Ma. We believe this is the main reason for the difference between our reconstruction and SG12 in the period between 15 and 5 Ma.

**Discussion**

We compare rates of trench-perpendicular and trench-parallel convergence against the tectono-magmatic evolution of the Andean margin (Fig. 3). These rates were computed for a fixed trench axis (see Supplementary Figs. S2A–C for alternatives considering an evolving trench axis). We focus our analysis on the most relevant and novel features revealed by this comparison, with emphasis in the Mid-Late Miocene evolution associated to the Quechua tectonic phase.

A convergence speedup after the birth of the Nazca plate coincides with the opening of Late Oligocene to Early Miocene extensional basins southward of 28°S13,44,45. Upper plate extension has been related to an enhanced slab pull and associated rollback as the Nazca slab freely penetrates the upper mantle43–47. Basins of this type were absent at 20°S (ref. 2), perhaps because trench-perpendicular convergence during the Late Oligocene was higher here than southward. Peak convergence rates during the Early Miocene coincides with the beginning of compressive inversion of the Oligo-Miocene extensional basins. This has been
explained as the consequence of the Nazca slab reaching the mantle discontinuity at 660 km depth and getting anchored in the more viscous part of the mantle, which could trigger a stronger coupling with the overriding plate for the rest of the Neogene. At the Altiplano latitude, this restructuration of the subduction system is associated to a lateral expansion of the area that deforms under a pure-shear mode from the center of the plateau to its flanks, although shortening rates remain at the moderately high values observed before 20 Ma.

High trench-perpendicular convergence rates prevailed until 16 Ma in the central and southern transects and until 14 Ma in the north. A rapid convergence deceleration then took place over the Middle Miocene, coinciding with notable changes in the activity of fault systems and magmatic arcs along the entire margin. At 40°S, an eastward migration of the deformation locus seems to be accompanied by a gap of the magmatic arc, whereas at 30°S the volcanic arc and deformation front start migrating eastwards. This is related to the beginning of slab shallowing at this latitude, a gradual increase of shortening rates across the margin, and the initiation of very rapid shortening in the Precordillera fault-thrust belt at 20°S.

At 20°S, the convergence deceleration at 15–14 Ma seems to coincide with the simultaneous activation of fault systems inside and at both flanks of the Altiplano. This could be the cause of an increase of orogen-wide shortening rates during the Middle Miocene, although rates estimated exclusively in the retroarc remain constant or even lower than previously. Whatever the case, the Middle Miocene deceleration of convergence was accompanied at the Altiplano latitude by a rapid surface uplift, from a paleo-elevation around 1.5 km before 15 Ma to 2.5–3.5 km near 13 Ma. This has been linked to delamination of lithospheric mantle and eclogitic lower crust and the initiation of very rapid shortening in the Precordillera fault-thrust belt at 20°S.

A sudden acceleration of convergence took place along the entire margin at the beginning of the Late Miocene, with high rates (ca. 14 cm/yr) prevailing during a short period of time between 11 and 9 Ma. This correlates with a westward shift of compressive deformation back to the Patagonian Cordillera and a short phase of renewed magmatism at 40°S. At 30°S, an eastward expansion of the volcanic arc is documented in synchrony with a rapid propagation of the deformation front inside the Precordillera at extreme shortening rates near 20 mm/yr (ref. 57). Peaks in orogen-wide shortening rates are documented at this time across 30°S (ref. 56) and 20°S (ref. 31), as well in the retroarc region behind the Altiplano. The latter is associated to an eastward shift of deformation into the Subandean fold-thrust belt, dramatically changing the crustal-scale deformation mechanism from distributed pure-shear to localized simple-shear. This is followed by an ignimbritic flare-up inside the Altiplano, attesting to a thermally-activated melting of the lower-mid crust, and the achievement of present-day topography and crustal thickness.

After the paroxysm of the Quechua phase in the earliest Late Miocene, shortening rates drop at 30°S and 20°S whereas convergence rate seems to decrease in two steps at 9 Ma and then at 7 Ma. This coincides with the installation of hyperarid conditions at the cordilleran western flanks as a consequence of the rain shadow effect created by the uplifted cordillera. No erosion means minimal unloading of forearc fault systems that remain largely inactive. According to the simple-shear mode of plateau growth, the rigid forearc then experienced passive uplift via trench-ward tilting as a response to thickening of the weak lower crust that is pushed by the westward underthrusting of the Brazilian shield below the Subandean system. The eastern side of the orogen concentrates most of the moisture coming from the Amazonas after 5 Ma, meaning enhanced erosional unloading of the fault-thrust belt and concentration of deformation. An acceleration of shortening rates during the Pliocene at 20°S and 30°S has been related to a climate-driven change toward more humid conditions around 5 Ma. The associated thickening of weak lower crust is likely redistributed by lateral crustal flow and not transferred to the forearc, which could explain why convergence velocity have remained notably stable over the last 5–7 Myrs along the entire margin.

The fundamental reasons explaining the observed correlation between variations in convergence and Andean tectonic evolution remain to be investigated. We attempt a preliminary analysis to elucidate whether the kinematic changes are related to the absolute motion of either plates or both, to highlight the first order features of the forces causing such changes.

We use finite rotations described above to calculate trench motions of Nazca and South America relative to Antarctica, which features a slow absolute motion during the Neogene and thus it arguably resembles an absolute reference frame. Figure 4 demonstrates that most of the changes in convergence between Nazca and South America during the Neogene are due to the absolute motion of the oceanic plate. This is in agreement with global-scale kinematic plate models at low temporal resolution that also show changes in Nazca-South America convergence under a relatively fixed position of the continental plate with respect to the mantle reference frame.

In particular, this indicates that the main difference between our reconstruction and SG12 (i.e. the pattern of convergence deceleration and acceleration coinciding with the Late Miocene Quechua phase) owes ultimately to the Nazca–Antarctica portion of the plate circuit. In this context, there are two aspects worth mentioning in order to lend support to this specific feature of our reconstruction:

i. This pattern of temporal changes of motion is not an artifact arising from the specific temporal resolution at which we interpolate finite rotations and reconstruct motion. In fact, such a pattern remains clear also when we reconstruct the Nazca–Pacific–Antarctica motion at different temporal resolutions (see Methods and Supplementary Figure S3).

ii. There is independent evidence that such changes indeed occurred. In fact, the spreading rate of the Chile Rise between 37°S and 46°S (Fig. 4A) has been directly observed from 17 cross-ridge magnetic lines and exhibits a temporal pattern of changes that is in line with our reconstruction. The agreement remains regardless of the temporal resolution utilized in our reconstruction, particularly when the same resolution as the original data is used (see Methods and Supplementary Figure S3). Furthermore, the short-lived change in Nazca–Antarctica azimuth between ~14 and ~12 Ma that we reconstruct through the Nazca–Pacific–Antarctica circuit is consistent with a ~10° counterclockwise change around 16 Ma in the direction of the Chiloe and Guayo fracture zones originally mapped using ocean-floor observations (Fig. 4B). Lastly, most fracture zones mapped around the Chile Rise from vertical gravity gradients (VGG) also exhibit a similar short-lived change in direction, although the length of the expected differently-oriented portions of fracture zones is close to the limit imposed by spatial resolution and uncertainty of the VGG-mapped fracture zones (see Methods and Supplementary Figure S4).

Accepting that Neogene changes in plate convergence are mostly due to variations in the absolute motion of the Nazca plate, and based on methods and analytical equations derived in
previous studies\textsuperscript{68,69}, we generate an ensemble of one million samples of the torque variation needed to explain the main kinematic changes of Nazca during the Mid-Late Miocene (Fig. 5). This represents an estimate of the magnitude and orientation of the additional torque established upon Nazca that caused its kinematic change, and that accounts for the uncertainties in the reconstructed plate motions. The torque variation during the Latest Miocene deceleration (8–5 Ma) is similar to the changes needed for the Middle Miocene slowdown (15–12 Ma), and both are virtually opposite in sign and almost equal in magnitude to the variation associated with the main Quechua acceleration (11–9 Ma). This consideration suggests that the kinematic energy gained by Nazca through the syn-Quechua acceleration is later converted (via crustal shortening and thickening) into GPE that is stored in the crustal root, resulting thus in the post-Quechua deceleration.

Simple analytical calculations (see Methods) allow us to infer that the estimated magnitudes of torque variations during and...
after the main Quechua acceleration are consistent with—and thus could in principle be caused by—changes of around 5E11 N/m in the slab pull force, or changes near 0.3 MPa in basal shear tractions underneath Nazca. Furthermore, they could also correspond to a change of the friction coefficient of the order of 0.03 occurring uniformly along the entire brittle megathrust, or around 0.1 if this occurred along the interplate fault in front of the central Altiplano-Puna segment. Although simplistic, these analyses indicate moderate changes of dominant forces that could be related to rather rapid, yet plausible variations in the dynamic coupling between the Nazca plate/slab with the upper mantle and/or resistance along its boundary with the upper plate.

In this scenario, changes in the main driving or resisting forces of Nazca would be the main cause of the associated tectonomagmatic events recorded along the continental margin. However, the high temporal resolution of our model allows to observe that the Middle Miocene deceleration does occur shortly after the suggested delamination event at 15–14 Ma (Fig. 3). It can be argued (Methods) that if the gain in GPE caused by delamination was laterally compensated by increasing shear tractions at the megathrust, then the torque variation upon Nazca could be in the range between 2-6E25 Nm. This range is indeed compatible with the histograms shown in Fig. 5A, which supports the plausibility of such a mechanism. Independently of the possible direct effect on convergence deceleration, delamination likely has an indirect but relevant role on the subsequent main Quechua acceleration at the beginning of Late Miocene (11–9 Ma). The post-delamination thermo-mechanical weakening of the mid-lower crust underneath the Altiplano led to a loss of mechanical strength that is related to a notable strain localization towards the Subandean fold-thrust belt31. In our view, this lithospheric-scale failure beneath the Central Altiplano-Puna segment. Although simplistic, these analyses indicate moderate changes of dominant forces that could be related to rather rapid, yet plausible variations in the dynamic coupling between the Nazca plate/slab with the upper mantle and/or resistance along its boundary with the upper plate.

Estimate of torque-variations required for plate-motion changes. Previous studies68,69 provided equations to calculate the torque-variation necessary upon a tectonic plate in order to generate a reconstructed kinematic variation. Specifically, by differentiating the torque-balance equation at two distinct moments in geological time, one obtains a relationship where the torque-variation vector is linked to the Euler-vector change through a linear map that depends on (i) the shape of the tectonic plate, and (ii) the ratio between viscosity and thickness of the underlying asthenosphere (see equations in68). Here we utilize the shape-files of Nazca put forth by the Earthbyte initiative (www.earthbyte.org) at the stages indicated in the Supplementary Information. Furthermore, we assume a viscosity of 5E19 Pa.s, in line with previous inferences derived from modelling of glacial isostatic adjustment data71. The thickness of the asthenosphere (here set to 150 km) is
determined from the relationship linking it to the asthenosphere viscosity contrast relative to the upper mantle\(^1\), whose viscosity here is assumed to be the Haskell-like value of \(1.5 \times 10^2\) Pa s. Such a relationship is inferred from the fit of glacial rebound models to long-wavelength rebound data. We utilize the equations above in order to convert ensembles of one million samples of the Euler-vector change drawn from our reconstruction of Nazca–Antarctica relative motion (Fig. 4) into ensembles of torque-variations, of which are shown in Fig. 5.

**Simple analytical estimates of dominant controls associated with torque-variations.** Generally speaking, the dominant controls on plate-motion changes can be either plate-boundary forces or shear stresses at the base of the plate. Therefore, in order to make a first-order estimate of force variations, one shall divide the torque-variation magnitude estimated from our kinematic reconstructions by the product of Earth’s radius with (i) the length of the tectonic margin where plate-boundary forces are assumed to change, or alternatively (ii) the basal area of the plate. The Nazca convergent margin between 15 and 5 Ma featured a length of around 6.5°E6 m, while the Nazca basal area was around 1.5°E13 m\(^2\). The majority of the Mid-Late Miocene torque-variation samples are in the range 1E25 to 1E25 Nm (Fig. 5A lower panel). If these were caused by changes in forces acting along the Andean convergent margin, then such changes must have been in range from 3E11 to 9E11 Nm. These could be directly associated to changes in the net slab-pull force and/or to changes in the frictional resistance along the brittle margin. In the latter case, the force-variation would require a change in the coefficient of friction in the range from 0.01 to 0.65 along the entire length of the brittle plate (assumed to extend to a depth of around 30 km). The estimated change in friction coefficient scales linearly with the length of the margin where friction varies. Therefore, assuming that the coefficient of friction changed only along the sediment-starved Central Andean margin this would yield an estimate for the change in friction in the range between 0.03 and 0.15. Instead, if the torque-variations were caused by changes in Nazca basal shear stresses, then such changes must have been in range from 0.1 to 0.5 MPa. Lastly, if one assumes that delamination of the thick and dense Andean crust and upper mantle generates uplift, then the GPE gain associated with such uplift must compensate for the change in buoyancy of the delaminated region and the lithospheric mantle material. Thus, the force exerted upon Nazca would be at most equal to the change in buoyancy associated with the delamination process. The buoyancy change depends on the volume of delaminated material and its density contrast with the mantle wedge. An estimate\(^21\) of the cross-sectional area of removed material at 20°S is of the order of \(30,000 \text{ km}^2\), resulting from a delaminated region that is 80 km thick and 350 km wide. A summary of previously published seismic models\(^26\) allows to infer a minimum along-strike extension of 200 km for a region of main Andean phases in a weak upper plate. Tectonophysics *721*, 151–166 (2017).

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### Data availability

All data used in this study are referenced and compiled as a database that is available in the Supplementary Information as Source Data Files.

### Code availability

Codes used in this study are referenced.

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Author contributions
G.I., O.R., and A.T. conceived and developed the main ideas and designed the study, F.Q. and G.I. compiled the finite rotations database and performed the plate kinematic reconstruction. G.I. computed torque-balance calculations. G.I. and A.T. calculated forces. A.T. created and edited main figures and wrote the main text. All authors collaborated in writing and revising the manuscript.

Competing interests
The authors declare no competing interests.

Additional information

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