



Plate motion drivers: Geodynamical framework and statistical appraisal for the case of the Neogene Nazca–South America convergence

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ABSTRACT

Recent high-resolution reconstructions of plate motions reveal a complex history of alternating slowdowns and speedups, often over short timescales (<5 Myr). These rapid changes offer an opportunity to reassess the geodynamic processes driving tectonic plates, which we explore using an analytical inverse framework. This approach, however, inevitably yields non-unique solutions when inferring the forces behind a motion change. We partly address this issue by focusing on forces capable of varying at rates consistent with rapid kinematic shifts, though the specific driver behind any change may remain ambiguous. We adopt a two-step methodology, using torque changes as intermediaries linking force variations to reconstructed absolute plate-motion changes. First, we employ an established method that combines rheological constraints with torque-balance principles to estimate the torque variation required for a given kinematic change. Second, we estimate torque-change vectors arising from a broad range of geodynamic scenarios — acting at plate boundaries (e.g., slab pull, interplate friction) and at the base of plates (e.g., asthenospheric flow). We then apply directional statistics to quantify the similarity between the motion-based torque-change distribution and each simulated vector. This comparison allows us to identify the location and direction of the force-change vectors most likely to produce the motion change of study. We apply this method to the Neogene Nazca–South America convergence. Our kinematic analysis reveals rapid slowdowns in the absolute motion of both plates and a pronounced Nazca speedup at ~10–12 Myr. Our geodynamic analysis indicates that the force variations driving the slowdowns are likely concentrated along the central segments of the shared convergent boundary. This result aligns with established hypotheses linking reduced convergence to Central Andes orogeny, thereby supporting our approach. Key advantages of this novel method include fast computation, explicit treatment of kinematic uncertainties, and broad applicability across tectonic settings.

1. Introduction

The Earth's surface is continuously reshaped by the relative motion of tectonic plates. Recent advances in the resolution of plate motion reconstructions (e.g., Croon et al., 2008; DeMets and Merkouriev, 2019) have enabled the identification of closely-spaced periods of slowdowns and speedups in the relative motion of plates. Such kinematic changes are ultimately governed by the interplay of deep mantle stresses and shallow plate-boundary forces (Forsyth and Uyeda, 1975; Iaffaldano and Bunge, 2015; Molnar and Stock, 2009), which are induced by a range of physical processes like brittle friction, viscous shearing,

and buoyancy contrasts. These forces include the pull of subducting slabs (*slab pull*; Conrad and Lithgow-Bertelloni, 2002; Faccenna et al., 2012; Schellart, 2004), the potential energy gradient created by the high topography of newly-formed oceanic lithosphere (*ridge push*; Forsyth and Uyeda, 1975; Lithgow-Bertelloni, 2016), the frictional resistance at the subduction interface (*subduction-interface friction*; Iaffaldano et al., 2006), and the resistive viscous shear exerted by the underlying mantle (*mantle drag*; Bercovici, 2003), among others.

Early efforts to understand plate dynamics concluded that the rate of plate motion is largely controlled by the rheology of the underlying

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mantle (e.g., Bercovici, 1995; Tackley, 1998). Furthermore, and given the mantle's high viscosity, plates are expected to adjust to dynamic changes virtually instantaneously (Iaffaldano and Bunge, 2015). This behavior underpins the widely used principle of force balance (e.g., Forsyth and Uyeda, 1975), which posits that the sum of forces acting on a plate must be zero at any given time. Even then, both analytical and numerical estimates of these forces often return a non-negligible residual (e.g., Clennett et al., 2023) or balance at plate velocities that deviate from those inferred by kinematic reconstructions (e.g., Conrad and Lithgow-Bertelloni, 2004). In analytical models, these mismatches may stem from uncertainties in key parameters (e.g., mantle viscosity) or from ambiguities regarding the effective contribution of individual forces to plate motion. For example, only a fraction of the available slab pull force may effectively contribute to the plate's horizontal motion, as an unknown – yet potentially substantial – portion is expended in bending the slab at the trench (e.g., Buffett, 2006).

Rather than addressing each individual force in balance at any given time, one can instead focus on the subset of forces that may evolve over finite time intervals (e.g., Iaffaldano and Bunge, 2015). Over timescales of a few million years, many driving and resisting forces can be reasonably assumed to remain steady, allowing the analysis to concentrate on those few likely to drive rapid changes in plate kinematics. For instance, the ridge push force per unit length primarily depends on the density structure of the oceanic lithosphere (Lister, 1975), which is not expected to change significantly over the lifetime of a plate (England and Molnar, 2022). However, the net contribution of this force (i.e., integrated over the divergent boundary) can still be modified by changes in the plate's geometry. A similar argument can be drawn for the mantle drag force, as its magnitude depends on slowly-evolving viscosity patterns within the Earth's mantle (Bunge et al., 1998) — provided that no significant change in plate area occurs.

In contrast, certain forces have the potential to experience abrupt, short-term fluctuations (within up to a few million years). Take for example the asthenosphere – the comparatively low-viscosity uppermost mantle layer – which can host rapid, pressure-driven changes in viscous flow (Höink and Lenardic, 2008; Mitrovica, 1996), allowing it to exert correspondingly rapid influences on plate motions (Stotz et al., 2018; Vilacís et al., 2022). These pressure variations may arise from transient convective processes in the mantle, including thermal downwellings (e.g., subducting slabs; Höink and Lenardic, 2010) and upwellings (e.g., rising mantle plumes; Phipps Morgan et al., 1995), as well as other localized, time-dependent geodynamic events such as lithospheric delamination, slab detachment, or changes in plume flow. Recent evidence for plume-driven shifts in plate motion spans diverse tectonic realms, including the Indian, North American, and South American plates (Cande and Stegman, 2011; Stotz et al., 2021, 2023; Wang et al., 2024).

Processes associated with the subducting slab provide another source of fast-paced changes to the geodynamic force balance. Slab dynamics can modify several key forces — including mantle drag, subduction-interface friction, and, most importantly, slab pull. Rapid fluctuations in slab pull, for instance, can arise from mechanisms such as slab detachment (Davies and Von Blanckenburg, 1995; Duretz et al., 2012; Garzanti et al., 2018; Hu et al., 2022), buckling (Pons et al., 2022; van der Wiel et al., 2024) or segmentation (Li et al., 2024). The latter two processes, in particular, may produce quasi-cyclic behavior over timescales comparable to the kinematic speedup–slowdown episodes investigated in this study.

Of particular relevance to the case study of South American convergence are changes in the frictional resistance along the subduction interface. These may arise from (i) variations in the friction coefficient due to changes in sediment supply, which affect the lubrication of the subduction channel (e.g., Hu et al., 2021; Zhou et al., 2024); (ii) changes in the vertical load above the interface, for example triggered by orogenic uplift (e.g., Austermann and Iaffaldano, 2013; England and Molnar, 2022; Iaffaldano et al., 2006; Molnar and Stock, 2009); (iii)

localized heterogeneities on the surface of the subducting plate, such as seamounts, fracture zones, ridges and plateaus (e.g., Domínguez et al., 1998; Rosenbaum et al., 2005; Suchov et al., 2022); or (iv) events such as slab rollback or slab flattening (e.g., Axen et al., 2018), which might impact the geometry of the subduction interface.

The geologic record documents numerous plate reorganization events, illustrating that significant changes in plate motion can occur as a result of diverse geodynamic processes affecting one or several tectonic forces. For example, the late Neogene collision of the Ontong Java Plateau with the Melanesian trench caused a brief westward drift of the Australian Plate (Knesel et al., 2008) and a counterclockwise rotation of the Pacific Plate (Wessel and Kroenke, 2000). In other cases, however, multiple geodynamic processes may be plausible candidates for driving a given plate motion change, or could even operate concurrently. For instance, the push of the Réunion plume (Cande and Stegman, 2011), the formation of double subduction zones (Jagoutz et al., 2015), and passive-margin sediment subduction (Zhou et al., 2024) have all been proposed to explain the acceleration of the Indian Plate around 65 Ma.

Although the processes outlined above are not exhaustive, their diversity highlights the need for approaches that account for varied geodynamic processes. In that context, numerical modeling stands out as a prevalent and powerful tool for unraveling the main driving mechanisms of plate tectonics, well-suited to incorporate complex dynamic processes (e.g., Lithgow-Bertelloni and Richards, 1995). This forward approach uses various physical constraints to estimate the forces acting upon tectonic plates and simulate the resulting plate kinematics, which are compared to empirical plate motion reconstructions through iterative validation (e.g., Conrad and Lithgow-Bertelloni, 2002; Stadler et al., 2010). However, forward modeling presents significant challenges, often requiring extensive knowledge of both present and past geological conditions, as well as a high computational cost. Furthermore, while simplified two-dimensional simulations can reduce this burden, they inherently sacrifice capturing three-dimensional mantle convection and plate motion. Although recent Bayesian approaches can formally incorporate observational errors (e.g., Ratnaswamy et al., 2015), the computational cost of forward modeling makes it currently infeasible to explore the full range of uncertainties in reconstructed plate motions.

Alternatively, an inverse approach can be applied, whereby plate motion reconstructions are used to calculate the force changes driving past kinematic variations. The challenge lies in the fact that any given change in plate motion can, in theory, be explained either by infinitely many plausible force changes yielding the same torque-change vector, or by infinitely many combinations of force changes acting simultaneously. This inherent non-uniqueness has long constrained the usefulness of the inverse approach.

One way to overcome this issue is to leverage sufficiently rapid plate-motion changes, as these could reasonably be attributed to a single force change. While reconstructions of relative plate motions (RPMs) already provide evidence of such rapid changes, absolute plate motions (APMs; i.e., defined relative to a deep-seated reference frame) remain less well constrained. Over geological timescales, APMs are typically reconstructed from intraplate volcanism along hotspot tracks (Dobrovine et al., 2012; Wessel and Kroenke, 2008), which yields a temporal resolution that is coarser than that of RPMs. An alternative approach, introduced by Iaffaldano and DeMets (2016) and later expanded by Espinoza and Iaffaldano (2023), involves comparing rapid changes in RPMs across neighboring plate systems and inferring the APM changes required to reconcile them. This method can only be applied to periods of kinematic change, but it has the advantage of inheriting the higher resolution and better-constrained uncertainties of RPMs.

In this study, we present a novel approach to evaluate the plausible forces behind rapid changes in plate motion. Our case study focuses on the Late Neogene (<20 Ma) convergence between the Nazca (NZ) and South American (SA) plates, a period traditionally linked to the

uplift of the Andean Cordillera. As a first step, we use highly resolved kinematic reconstructions of NZ and SA (Espinoza and Iaffaldano, 2023; Quiero et al., 2022) to identify and calculate the rapid APM changes experienced by both plates. We describe the plate kinematics using Euler vectors (Cox and Hart, 1986; Gordon, 1998) and cast them into the torque-balance equation (e.g., Espinoza et al., 2024; Iaffaldano and Bunge, 2015; Martin de Blas and Iaffaldano, 2019), thereby linking changes in plate motion to the torque variations required to drive them. Simultaneously, we simulate scenarios involving plausible changes in the forces acting on the margins and base of SA and NZ, calculating the corresponding torque-change vector for each scenario. By statistically comparing these vectors with those derived from the reconstructions, we estimate the likelihood that each scenario can explain the reconstructed APM changes. This approach enables us to identify the geological processes most likely responsible for the reconstructed plate motions, considering their timing, magnitude, orientation, and location.

The South American orogeny serves as a case study to illustrate the utility of this newly developed methodology, which we outline in the following sections. More detailed and technical aspects of the methods are reported in the Supplementary Material for completeness and reproducibility. The code used for the main analysis is written in Python and openly shared via Zenodo (see Data Availability), enabling readers to explore alternative parameter choices if desired.

2. Methodology

2.1. Kinematic reconstruction of absolute plate motions (NZ and SA)

The recent study by Espinoza and Iaffaldano (2023) [ESP23] identified two episodes of slowdown in the absolute motion of the SA plate during the Late Neogene. These events took place at times ~ 15 –10 Ma and ~ 9 –5 Ma, amounting to a meaningful 13% and 20% reduction in angular velocity, respectively. A considerable fraction of these slowdowns stems from the motion of SA relative to a generally steady Nubia (NB). The SA–NB relative motion (DeMets and Merkouriev, 2019) is shown in the top panel of our Fig. 1 for visual reference, although we emphasize that only absolute motion changes were used for dynamic calculations in this study, as shown ahead.

A separate study by Quiero et al. (2022) [QUI22] revealed a history of sharp changes in the convergence between the NZ and SA plates over the last 27 Myr (Fig. 1, bottom panel). The timing of these events – two slowdowns and one speedup, which we refer here as focus periods A, B, and C – closely matches those described in ESP23. The oldest plate motion change identified for SA is labeled CB, since the same interval in NZ is subdivided into two focus periods (C and B) that exhibit distinct kinematic behavior: a slowdown followed by a speedup. Note also that the order of labels is presented in reverse chronological order. Firstly, we analyze plate-motion events from period A (~ 9 –5 Ma), and subsequently those of periods C, B and CB (~ 15 –10 Ma). Focus period A begins with the stage between reversals 4Ao (9.105 Ma; ages following the timescale GTS20 of Ogg, 2020) and 4n.2o (8.108 Ma), and ends with the stage between reversals 3An.1y (6.023 Ma) and 3n.4o (5.235 Ma). Focus period B is set to begin with the stage between reversals 5An.2o (12.474 Ma) and 5n.2o (11.056 Ma), and to end with the stage between reversals 5n.2o (11.056 Ma) and 5n.1y (9.786 Ma). Finally, focus period C begins with the stage between reversals 5ADo (14.609 Ma) and 5ACy (13.739 Ma), and ends at the stage between reversals 5An.2o (12.474 Ma) and 5n.2o (11.056 Ma). For simplicity, throughout this section these stages are labeled with numbers from 1 to 5 (see Fig. 1).

These stages closely match the periods considered by Quiero et al. (2022), who inferred NZ's APM changes from the relative convergence with SA, assuming SA's motion to be steady. In the present work, we further constrain NZ's APM by, whenever possible, subtracting the APM change of SA estimated in ESP23. To achieve this, all datasets have

been harmonized to a common magnetic reversals timescale, i.e., we reassigned the magnetic-reversal ages of the datasets used in QUI22 to the updated GTS20 timescale (Ogg, 2020), employed in ESP23. Furthermore, in a few cases interpolation was required in order to ensure consistent age boundaries across all our Euler-vector stages. Additional details on this harmonization and the datasets used can be found in the Supplementary Methods (Appendix A).

In general, the Euler vector describing the relative motion between two plates P1 and P2 can be expressed as the difference between their respective Euler vectors of absolute motion, $\vec{\omega}_{P1/P2} = \vec{\omega}_{P1} - \vec{\omega}_{P2}$. As a consequence: $\Delta\vec{\omega}_{P1/P2} = \Delta\vec{\omega}_{P1} - \Delta\vec{\omega}_{P2}$ and $\Delta\vec{\omega}_{P1} = \Delta\vec{\omega}_{P1/P2} + \Delta\vec{\omega}_{P2}$. To keep track of the stages involved, we use the aforementioned numbered-labels. For instance, $\Delta^2\vec{\omega}_{NZ/SA}^1$ is the motion change of NZ relative to SA from stage 2 to stage 1.

Then, we proceed to obtain the Euler vectors describing the absolute motion changes for both NZ and SA for the different focus periods. As already mentioned, absolute changes experienced by SA during the periods A and CB are directly extracted from ESP23:

$$\begin{aligned}\Delta\vec{\omega}_{SA}(A) &= \Delta^4\vec{\omega}_{SA}^5 \\ \Delta\vec{\omega}_{SA}(CB) &= \Delta^1\vec{\omega}_{SA}^3\end{aligned}\quad (1)$$

For the NZ plate, we need to perform some simple operations to obtain estimations of the absolute motion changes based on the QUI22 and ESP23 datasets. For focus period A (~ 9 –5 Ma), the procedure is straightforward, since the initial and final stages are meant to fit the already available $\Delta^4\vec{\omega}_{NZ/SA}^5$ (QUI22) and $\Delta^4\vec{\omega}_{SA}^5$ (ESP23).

$$\begin{aligned}\Delta\vec{\omega}_{NZ}(A) &= \Delta^4\vec{\omega}_{NZ}^5 \\ &= \Delta^4\vec{\omega}_{NZ/SA}^5 + \Delta^4\vec{\omega}_{SA}^5\end{aligned}\quad (2)$$

Focus period B (~ 12 –10 Ma) does not match the available SA estimate, as this actually encompasses the time spanned for focus periods C and B combined (~ 15 –10 Ma). In order to estimate $\Delta^2\vec{\omega}_{NZ}^3$, we assume (based on the stage ages) that SA has experienced half of its overall motion-change during this stage, i.e., $\Delta^2\vec{\omega}_{SA}^3 = 0.5 \cdot \Delta^1\vec{\omega}_{SA}^3$.

$$\begin{aligned}\Delta\vec{\omega}_{NZ}(B) &= \Delta^2\vec{\omega}_{NZ}^3 \\ &= \Delta^2\vec{\omega}_{NZ/SA}^3 + \Delta^2\vec{\omega}_{SA}^3 \\ &= \Delta^2\vec{\omega}_{NZ/SA}^3 + 0.5 \Delta^1\vec{\omega}_{SA}^3\end{aligned}\quad (3)$$

Finally, we proceed to estimate the NZ motion-change during focus period C (~ 15 –12 Ma) as follows:

$$\begin{aligned}\Delta\vec{\omega}_{NZ}(C) &= \Delta^1\vec{\omega}_{NZ}^2 \\ &= \Delta^1\vec{\omega}_{NZ}^3 - \Delta^2\vec{\omega}_{NZ}^3 \\ &= \left[\Delta^1\vec{\omega}_{NZ/SA}^3 + \Delta^1\vec{\omega}_{SA}^3 \right] - \Delta^2\vec{\omega}_{NZ}^3\end{aligned}\quad (4)$$

The resulting Euler-vector changes are reported in Supplementary Table 1 (Appendix B). It is important to recall that we consider the APM changes calculated for each plate to be independent of each other. Concerns may arise from the fact that both plate circuits share a common dataset — the relative motion between NB and SA plates. However, all changes reconstructed for the NZ–SA relative motion can be ratified as changes of NZ via the Chile Rise, i.e., the spreading boundary between NZ and the Antarctica plate. The work of Tebbens et al. (1997) reporting magnetic lineations collected across this particular ridge shows meaningful spreading-rate changes (within the 95% confidence) during focus periods A, B and C.

2.2. Calculating torque changes from reconstructed plate motions

In order to estimate the torque variation required on a given plate to produce a change in its reconstructed motion, we utilize the recently-developed software MYRIAM (Espinoza et al., 2024). Based on the principle of dynamic balance and knowledge of the rheological characteristics of the asthenosphere, this tool calculates the necessary torque

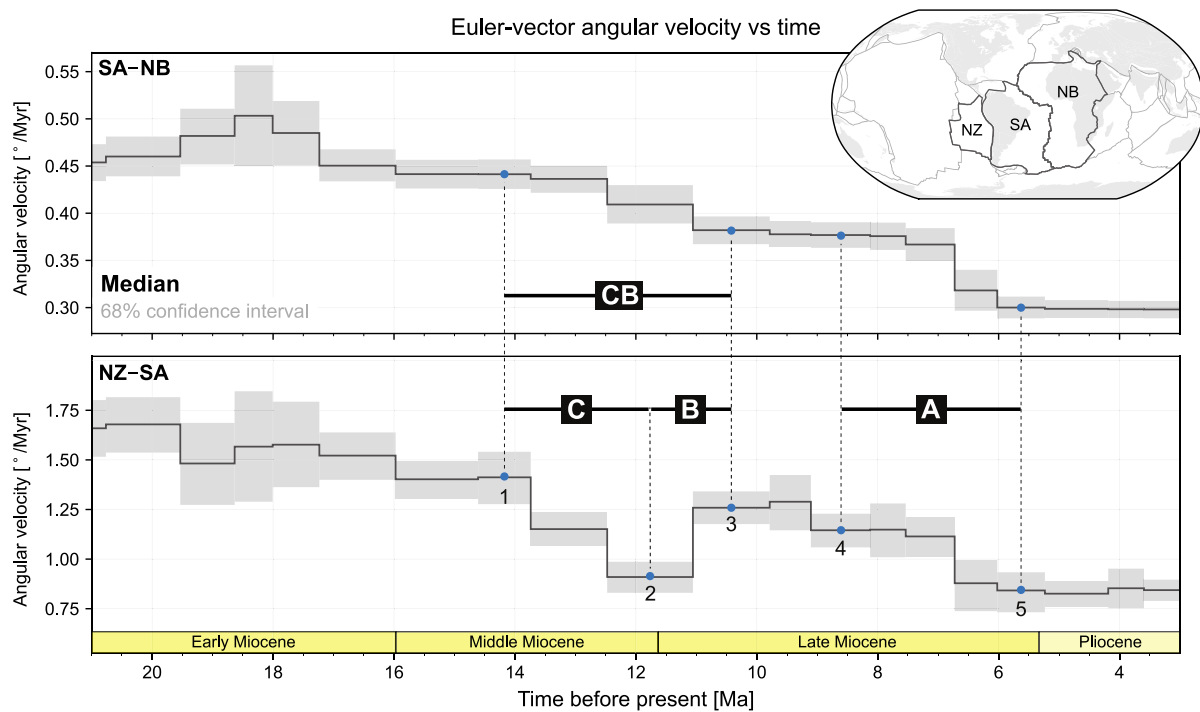


Fig. 1. Temporal variation of angular velocity for the reconstructed motion of South America relative to Nubia (SA–NB, top panel) and Nazca relative to South America (NZ–SA, bottom panel). The inset map shows the relative positions of all relevant plates, with plate boundaries reconstructed to 7.0 Ma, based on the model by [Matthews et al. \(2016\)](#). Euler vectors for SA–NB and NZ–SA are sampled from finite rotations in [DeMets and Merkouriev \(2019\)](#) and [Quiro et al. \(2022\)](#), respectively. Magnetic reversal ages are assigned using the geomagnetic polarity timescale GTS20 ([Ogg, 2020](#)). Solid lines represent the median value for the magnitude of sampled ensembles of 10^6 Euler vectors, while gray shaded areas indicate the 68% confidence interval for those ensembles. Blue markers indicate temporal stages of interest i.e., stages that represent either the beginning or the end of an identified motion change, which are numbered from one to five. Letters A, B, and C denote three specific time lapses which are the focus of our plate kinematics study. Label order is chronologically inverted (from younger to older), as per structure of the paper: C refers to the time span between stages 1 and 2, B between stages 2 and 3, and A between stages 4 and 5. Ages for all stages are detailed in the main text.

variation to overcome the viscous shear resistance exerted at the base of the plate (i.e., mantle drag) for a given change in plate motion. As such, the torque change that MYRIAM outputs shall be viewed as the net resultant of all torque changes – excepting mantle drag – acting on the plate. Note that the input Euler vectors of motion change are sampled one million times in order to account for the reported uncertainty in plate motion. As a result, the output is in fact a one-million-size ensemble of torque-variation vectors. In the Supplementary Methods, we report and reference the torque-balance equations implemented by MYRIAM for completeness and reproducibility.

MYRIAM performs a discretized calculation of the shear stress along the plate's lithosphere–asthenosphere boundary. Past plate contours of NZ and SA are reconstructed using the model of [Matthews et al. \(2016\)](#) at two representative ages: 11.5 and 7.0 Ma. The former represents the average plate shape for focus periods C and B, while the latter is used for the analysis concerning focus period A. Other relevant parameters in MYRIAM include a uniform lithosphere thickness of 180 km, an asthenosphere viscosity of $5 \cdot 10^{19}$ Pa s, and an upper mantle viscosity of $1.5 \cdot 10^{21}$ Pa s ([Colli et al., 2014](#); [Höink et al., 2011](#)). The average value for the viscosity of the asthenosphere is used internally to derive laterally varying viscosity values based on the tomographic mapping provided by [Priestley and McKenzie \(2013\)](#). The thickness of the asthenosphere is derived by MYRIAM following [Paulson and Richards \(2009\)](#), who established a proportionality relation between the viscosities of the asthenosphere and upper mantle in agreement with postglacial rebound data. We use then an asthenosphere thickness value of ~ 150 km based on the viscosity values above. The complete parameterization of the model can be found in the Supplementary Files (Appendix C). The resulting motion-based torque changes are reported in [Table 1](#) and displayed in Supplementary [Figs. 1, 2 and 3](#) (Appendix B).

As introduced earlier, this motion-based torque change could arise from any combination of force changes or from a single one. Events of different nature occurring in distant parts of the plate could contribute to this torque variation. Thus, the inverse problem of detecting geological processes responsible for specific (i.e., inferred from kinematic reconstructions) torque variations does not have a unique solution. However, since we are purposely dealing with relatively rapid (i.e., occurring over few Myr) motion changes, we deem reasonable to assume that these are generated by no more than one force varying at a time. Initially, we impose no constraints on whether our simulated force changes drive or resist plate motions, nor on the dynamic origin of the force in question (e.g., slab pull, friction). In fact, we initially simply focus on simulating multiple force-orientation scenarios that would account for variations in the most fundamental tectonic forces (see examples in [Forsyth and Uyeda, 1975](#)), including those acting at the boundaries as well as at the base of plates. Our analysis is primarily focused on torque orientations because, as noted in [Espinoza et al. \(2024\)](#), the orientation of the torque-change vector remains largely invariant to the parameters used to model the rheology of the underlying asthenosphere. In contrast, its magnitude can vary significantly and generally carries a greater uncertainty.

It is also worth noting that, aside from the assumptions outlined above, the approach implemented in MYRIAM entails certain limitations, including (i) the extrapolation of present-day mantle lateral variations to the geologic past, (ii) the assumption of a Newtonian mantle rheology, and (iii) the inability to account for lateral variations in lithospheric thickness, as MYRIAM's algorithm treats plates as flat and uniform. The latter reflects an inherent trade-off in MYRIAM's current level of simplification, whereas the first two are of very limited concern. In fact, the analyses presented here do not extend too far back in time

Table 1

Torque-change vectors necessary to produce the reconstructed absolute motion changes of the Nazca and South American plates, for the three focus periods analyzed by this study.

Moving plate	Focus period	Initial stage	Final stage	Long. [°N]	Lat. [°E]	Magnitude [10 ²⁴ N m]	Covariance elements [10 ⁴⁹ N ² m ²]					
							c_{xx}	c_{xy}	c_{xz}	c_{yy}	c_{yz}	c_{zz}
SA ^a	A	9.105 - 8.108 Ma (4Ao - 4n.2o)	6.023 - 5.235 Ma (3An.1y - 3n.4o)	-39.4	68.2	8.34	0.171	-0.022	0.275	0.149	-0.163	0.788
SA ^a	CB	14.609 - 13.739 Ma (5ADo - 5ACy)	11.056 - 9.786 Ma (5n.2o - 5n.1y)	-32.8	65.2	5.13	0.039	-0.015	0.082	0.037	-0.081	0.27
NZ ^b	A	9.105 - 8.108 Ma (4Ao - 4n.2o)	6.023 - 5.235 Ma (3An.1y - 3n.4o)	107.8	-70.05	14.78	6.982	-0.423	1.153	0.663	-1.438	3.833
NZ ^b	B	12.474 - 11.056 Ma (5An.2o - 5n.2o)	11.056 - 9.786 Ma (5n.2o - 5n.1y)	-102.6	66.9	21.2	6.705	-0.562	1.267	0.590	-1.356	3.934
NZ ^b	C	14.609 - 13.739 Ma (5ADo - 5ACy)	12.474 - 11.056 Ma (5An.2o - 5n.2o)	20.6	-46.2	31.1	11.6	-0.695	1.834	0.982	-2.419	7.029

^a From Espinoza and Iaffaldano (2023).

^b This work.

for average mantle conditions to have changed drastically (Bunge et al., 1998).

Furthermore, the integral nature of the torque-balance equation suggests that having assumed a simple Newtonian asthenosphere rheology over a more-realistic strain-rate-dependent one, does not significantly hamper our analysis. The torque change generated by mantle drag ultimately depends on the integral of basal shear stresses over the plate basal area (see Eq. 2 in Iaffaldano and Bunge, 2015). Following Newton's law of viscosity, these stresses scale with the product of depth-averaged asthenosphere viscosity and the local strain rate. Because we evaluate this over large plates, the integral effectively averages out local departures from Newtonian rheology behavior, thereby limiting their impact on the estimated basal shear stresses.

2.3. Simulating torque changes at plate boundaries

In order to analyze the force changes acting on plate boundaries, we once more utilize the reconstructed plate polygons put forth by Matthews et al. (2016). We use the midpoint of each boundary segment as the application point for a force-change vector acting on that segment (see Fig. 2), and explore two scenarios: (i) vectors oriented orthogonally to the boundary segments (Fig. 2a,b), and (ii) aligned parallel to the direction of the plate relative motion with respect to adjacent plates (Fig. 2c,d). In addition, vectors are directed inward (Fig. 2a,c) and outward (Fig. 2b,d), corresponding to positive and negative force changes, respectively. Case-specific interpretations will be addressed in the Discussion. However, as a reference, changes in inward-directed forces can reflect either an increase (positive change) in a *pushing* force (e.g., ridge push) or a decrease (negative change) in a *pulling* force (e.g., slab pull). Conversely, outward-directed force changes represent the opposite: a decrease in a pushing force or an increase in a pulling force. Note that force changes parallel to the direction of the relative motion are only calculated for the shared margin between NZ and SA. From each simulated force-change vector, we compute its cross product with the position vector of the corresponding segment midpoint to obtain the associated torque-change vectors. We perform these torque-change calculations for each scenario, for both SA and NZ, and for each of the three focus periods (A–C).

2.4. Simulating torque changes from asthenospheric flow changes

We also simulate force changes acting on the base of the plate, specifically those originated from a point of radially diverging/converging vectors (see Fig. 2e,f), which are meant to simulate the influence of a plume experiencing increasing/waning strength of flow. To this end, we use the hotspot compilation of Whittaker et al. (2015) in order to determine the net plume-flow pattern across the plate's area for each individual plume. Because our analysis does not extend far back in time,

we assume plume center locations have remained fixed relative to the present day (e.g., Wessel and Kroenke, 2008).

The parameterization of the added asthenospheric flow velocity component follows Iaffaldano et al. (2018), where the asthenosphere flow velocity V_{plume} at a distance Δx away from the plume center, at a given time t , is expressed as:

$$V_{plume}(t) = \frac{H_a^2}{8\mu_a} \frac{g \cdot \Delta\rho \cdot h(t)}{\Delta x}$$

where H_a is the asthenosphere thickness, μ_a its viscosity, with values matching those used by MYRIAM, i.e. 150 km and $5 \cdot 10^{19}$ Pa s. g is the gravitational acceleration constant (9.8 m s^{-2}), $\Delta\rho$ is the density contrast between the mantle and a displaced surface layer due to dynamic topography. We assume this parameter is equal to 3300 kg/m^3 for all hotspots considered in this study, taking the assumption that they are all subaerial ($\rho_{air} \simeq 1 \text{ kg/m}^3$, $\rho_{mantle} \simeq 3300 \text{ kg/m}^3$). h is dynamic topographic height induced by the plume influx. Δx is the geodesic distance away from the plume center.

The flow change between time t_1 and time t_2 (subsequent to t_1) can be expressed as:

$$\Delta V_{plume}(t_1, t_2) = \frac{H_a^2}{8\mu_a} \frac{g \cdot \Delta\rho}{\Delta x} [h(t_1) - h(t_2)]$$

We set $\Delta h(t_1, t_2)$ to 500 m for all plumes — a conservative value relative to the transient uplift of ~500–900 m reported for the Icelandic plume (Hartley et al., 2011).

As illustrated in Fig. 2, each scenario is evaluated over a grid of positions, but only those falling within the plate boundaries are considered. At each valid position, the force-change vector is scaled by the represented area and converted into a torque-change vector. The resulting array of torque-change vectors is then summed into a single vector that characterizes the plume-flow impact for that scenario. As with boundary forces, we perform torque-change calculations for each plume scenario (diverging and converging), for both plates and across all three focus periods.

2.5. Assessing the likelihood of each torque-change scenario

The orientation of the simulated torque-change vectors (hereafter *simulated* vectors) is compared with the motion-based torque-change vectors obtained from MYRIAM (hereafter *reference* vectors) using directional statistics. A statistical assessment of these simulated vectors against the reference vector ensembles requires estimating a probability distribution for the latter. The reference vectors arise from an ellipsoidal covariance distribution and can therefore be described using a few parameters, particularly the mean vector and the associated covariance elements. This simple parameterization does not hold if

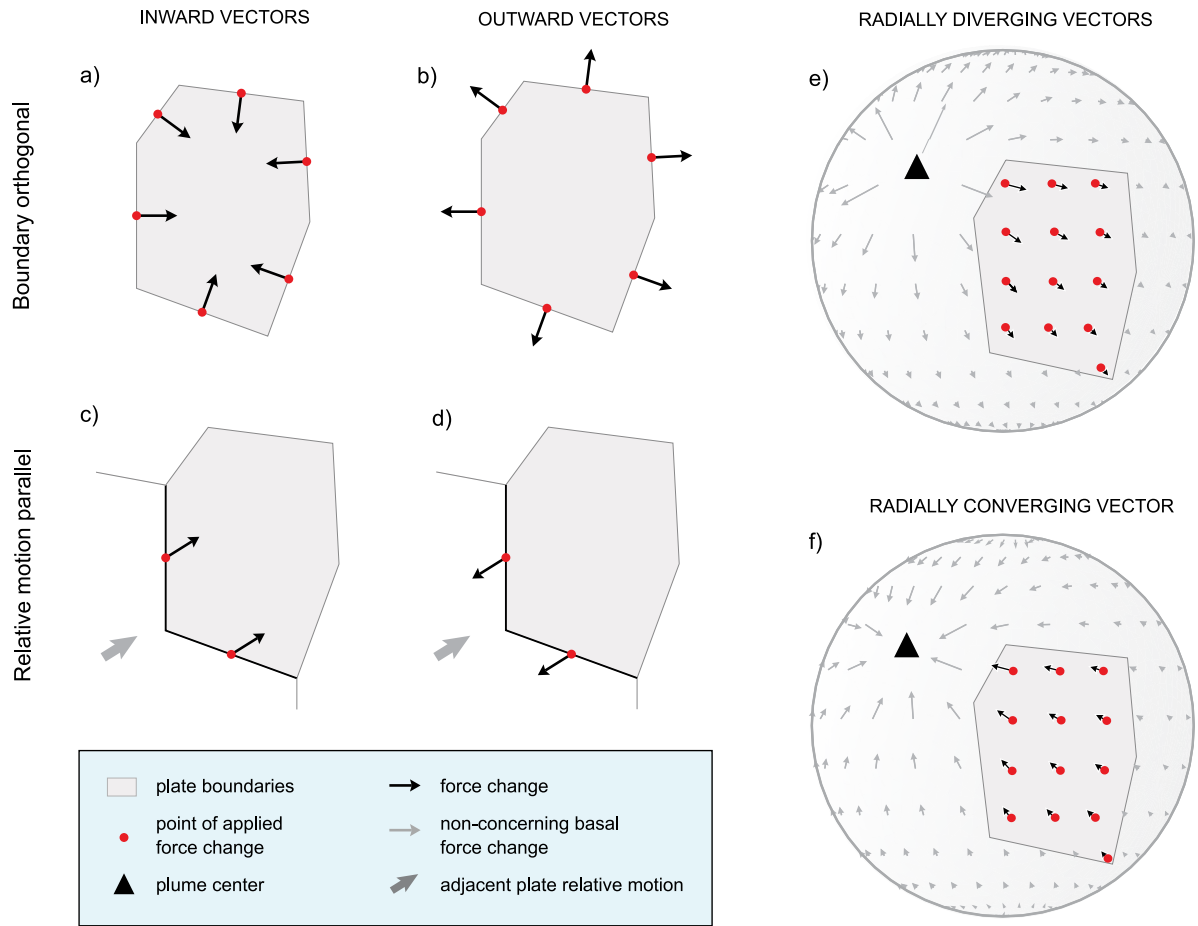


Fig. 2. Illustration of simulated force-change scenarios. (a)–(d) Sketch of a fictional tectonic plate shown as a gray polygon. Dark gray lines indicate plate boundary segments. Black arrows represent the simulated force-change vectors whose locations and orientations are defined according to the criteria applied in this study. Red dots mark the midpoints of each boundary segment, where the vectors originate. In panels (a) and (b), vectors point orthogonal to each segment, directed inward and outward, respectively. In panels (c) and (d), vectors align with the relative motion of the adjacent plate (large gray arrow) and are calculated only for the subsections that form shared boundaries. In this case, vectors are also tested pointing either inward or outward along the shared boundaries. (e)–(f) Sketch of radially divergent and convergent forces acting at the base of a fictional plate (gray polygon). The black triangle marks the plume center, whose location determines the flow pattern and vector orientations. Vector magnitudes are set to increase with proximity to the plume. Gray arrows represent vectors that lie beyond the plate boundaries and are therefore excluded from the net torque-change calculation, as described in the main text.

we focus solely on the vectors orientations, i.e. the projection of the 3D vectors onto a unit sphere (see Supplementary Figure 4). We deliberately chose to isolate the vectors orientation from its magnitude since, unlike orientations, magnitudes are highly dependent on the rheological properties of the model passed onto MYRIAM.

Probability distributions commonly used in directional statistics, such as the Fisher or Kent distributions (Mardia and Jupp, 2009), do not describe skewed data, which may be the case for the projection of a strongly asymmetric covariance matrix (see Supplementary Figure 4). For this reason, we have chosen to use a Kernel Density Estimator (KDE) based on a Fisher distribution kernel to produce a probability density distribution for the orientations of the reference vectors. Since the computing time for this technique grows exponentially with sample size, we use a sub-sample of 10,000 vectors to generate each KDE.

Then, we use the cumulative distribution of the KDE to obtain a probability value for the direction of each simulated vector from the previous sections. The probability value is interpreted as the likelihood value, a probability that measures the similarity between a simulated vector and the reference KDE distribution. Consequently, this likelihood quantifies the probability that a reconstructed kinematic change in a tectonic plate was driven by a specific force-change scenario (see example in Fig. 3).

3. Results

Figs. 4 and 6 show the case in which we analyze force changes applied along the boundaries of the SA and NZ plates. The different panels illustrate the cases in which the force-change vector is applied orthogonal to the plate margins, or parallel to the direction of relative motion between the plates. For each case, we also explore the possibility that these vectors are oriented either inward or outward. Boundary segments are colored according to the calculated orientation likelihood, ranging from light green (low values of likelihood) to dark brown (high likelihood). The darker segments are of particular interest, as they indicate high-likelihood application points for force-change vectors.

Figs. 5 and 7 show the likelihood values for the scenarios in which plume-induced flow changes at the base of the plates may account for the reconstructed absolute motion changes of SA and NZ. The reference torque-change ensembles are shown in blue, with their mean vector orientation pole as a blue star and the 68%/95% confidence contours represented by solid and dashed lines, respectively. The globes in the left column represent plume-centered, radially diverging flow, simulating the effect of a strengthening plume. In contrast, the globes in the right column depict radially converging flow, akin to the effect of a weakening plume. Each plume center is marked by a triangle, with its color indicating the calculated orientation likelihood, following the

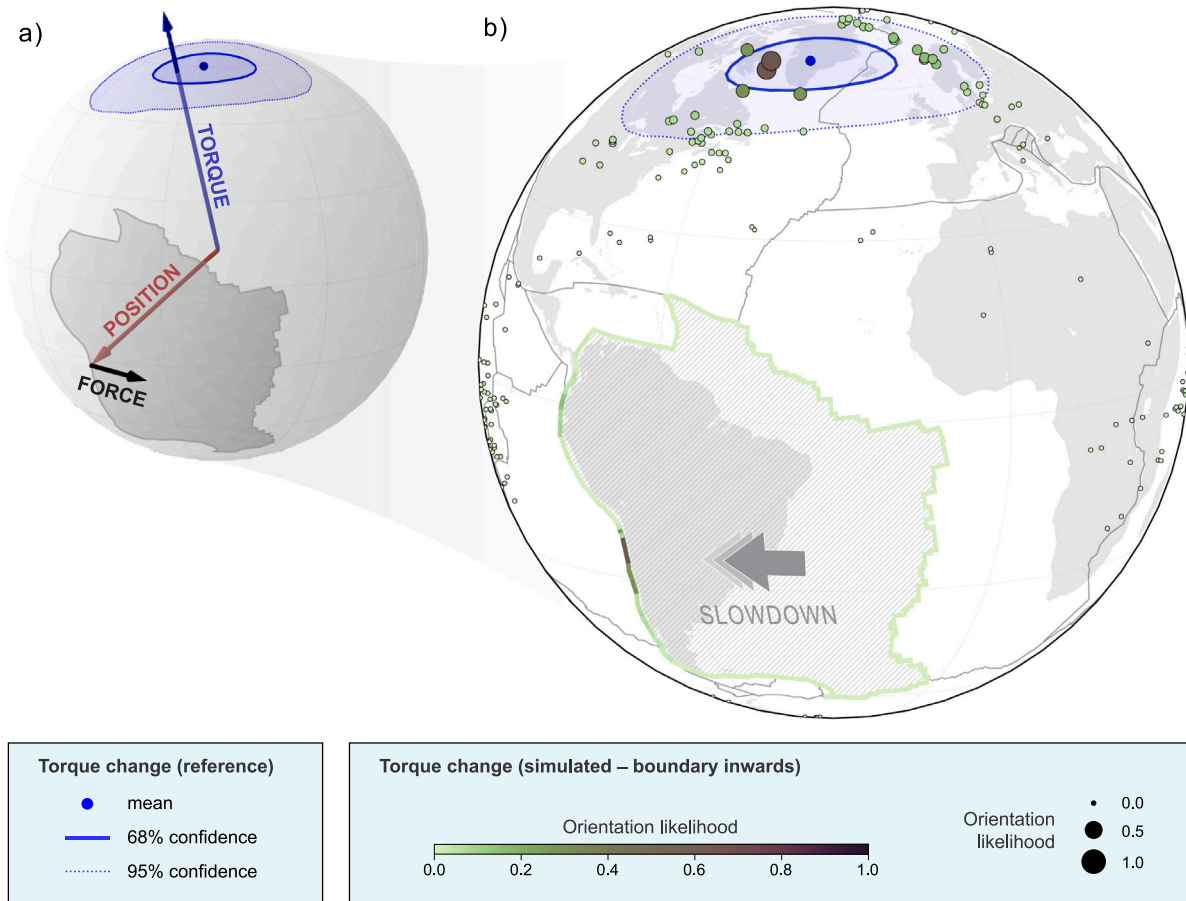


Fig. 3. Likelihood calculation for simulated torque-change scenarios. (a) Illustration of vectors on a sphere: position vector ($\vec{P}$, red), force vector ($\vec{F}$, black), and torque vector ($\vec{M}$, blue). Torques (or torque changes) are obtained as $\vec{P} \times \vec{F} = \vec{M}$. The blue dot and contours mark the mean, 68%, and 95% confidence intervals of the reference torque-change distribution required to reproduce the SA slowdown during focus period A (~9–5 Ma). The South American plate is shown in gray. (b) Likelihood calculated for simulated force-change vectors directed orthogonally inward, compared with the aforementioned reference distribution (blue contours). Colored round markers indicate the orientation of each simulated torque-change vector, with color and size representing the calculated likelihood: larger, darker markers indicate a closer fit to the reference distribution. Boundary segments adopt the same color as their corresponding torque-change vector; darker segments indicate that inward force-change vectors applied there are more likely to account for the SA motion change during ~9–5 Ma. Gray arrows illustrate the absolute motion change experienced by the plate; size and orientation of the arrows are arbitrary. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

same color scheme as Figs. 4 and 6. The size of the triangles indicates the magnitude likelihood, which is calculated from the torque-magnitude cumulative density function, scaled based on a conservative plume-induced dynamic topography change of 500 m (Hartley et al., 2011; Hoggard et al., 2016). We include both orientation and magnitude likelihoods to assist in the overall evaluation of each plume. For instance, plume centers located far away can still exhibit a high orientation likelihood (darker colored triangles) if their net torque-change orientations align with the reference torque-change ensemble. However, the net torque-change magnitude decreases with distance, meaning that plume centers farther away will be represented by smaller triangles due to the reduced likelihood associated with the torque magnitude. Similarly, plumes located near the plate's center may align in orientation with the reference torque, yet result in a near-zero net force change due to plume's radially symmetric flow. Since these plume-induced scenarios simulate a single, well-understood geological process, we provide an estimate for the torque-change magnitude. In contrast, estimates of magnitudes for the boundary forces – which may cover a wider range of processes – will be addressed in the Discussion.

On a different note, the torque magnitude required to produce the absolute kinematic change in NZ is, on average, at least twice

that needed for SA (see *Magnitude* column in Table 1). This implies that torque magnitudes for SA are more easily achieved by the tested plumes, making them more likely, and thus resulting in bigger triangle symbols overall. The likelihood estimates resulting from these scenarios shall be taken carefully, considering the sensitivity of both the simulated and reference torque-change magnitudes to the rheological parameterization of the asthenosphere and upper mantle. Lastly, the orientation/magnitude probabilistic analysis presented here does not account for the existence of geological features that may obstruct flow within the asthenosphere, such as slabs and cratons. Consequently, when interpreting our results we will highlight plume centers that meet the following criteria: (i) generate a flow that is not obstructed by the aforementioned geological barriers, (ii) present relatively high likelihood values in terms of orientation, (iii) present moderate to high likelihood values in terms of magnitude.

3.1. Focus period A (~9–5 Ma)

When examining the plausible force changes behind the reconstructed absolute motion change of SA during focus period A (~9–5 Ma, Fig. 4a–d), high-likelihood boundary segments (i.e., above 60%)

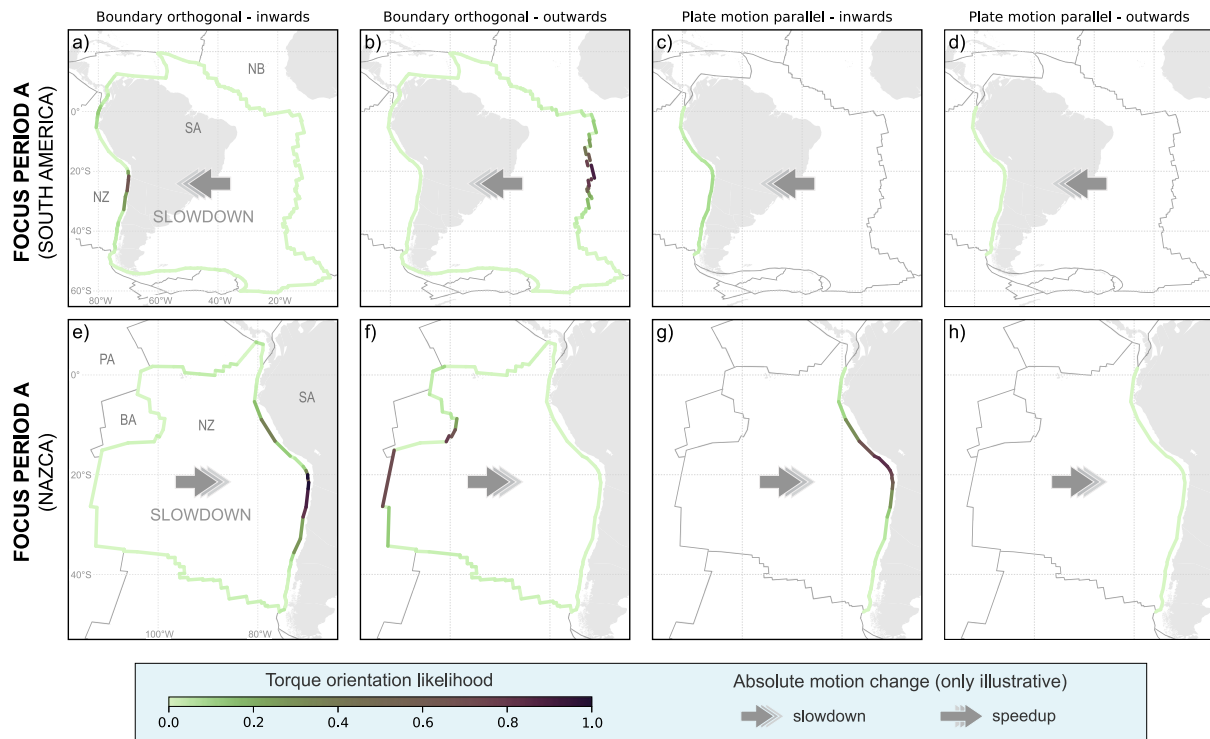


Fig. 4. Probability values indicating how likely the torque changes generated by force-change vectors at the NZ and SA plate boundaries are to match the motion-based torque changes during focus period A (~9–5 Ma). The top row (panels a–d) shows likelihood values for each boundary subsection associated with the absolute motion of the SA plate, while the bottom row corresponds to the absolute motion of the NZ plate (panels e–h). In the leftmost columns, force-change vectors are oriented orthogonal to plate margins, pointing inward (panels a,e) and outward (panels b,f). In the rightmost columns, force-change vectors are applied along the shared boundary between NZ and SA and oriented parallel to their relative plate motion, pointing inward (panels c,g) and outward (panels d,h). Low likelihood values are shown in light green, while high likelihoods are shown in dark green/black. Gray arrows illustrate the absolute motion change experienced by the plate; size and orientation of the arrows are arbitrary. Plate names are shown in gray capital letters; NZ: Nazca, SA: South America, NB: Nubia, PA: Pacific, BA: Bauer. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

are observed only for force changes oriented orthogonal to the plate boundaries (Fig. 4a,b). Specifically, high likelihoods occur along the NZ–SA convergent margin between latitudes 20°S and 30°S for inward-oriented force-change vectors, and along the SA–NB divergent margin between latitudes 10°S and 30°S for outward-oriented vectors. In contrast, force changes aligned parallel to the motion of NZ relative to SA, regardless of their inward/outward direction, show likelihood values below 10%.

For the NZ plate (Fig. 4e–h), high-likelihood segments are found for orthogonal-oriented force-change vectors (Fig. 4e,f) as well as for motion-parallel inward-directed vectors (Fig. 4g). High likelihoods occur (i) for inward orthogonal vectors along the NZ–SA convergent margin between latitudes 20°S and 30°S, (ii) for outward orthogonal vectors along the NZ–PA (Pacific plate) divergent margin between 15°S and 25°S and along the NZ–BA (Bauer microplate) margin between 12°S and 14°S, and (iii) along the NZ–SA convergent margin between latitudes 14°S and 21°S for inward-directed motion-parallel force-change vectors.

We then assess the potential influence of mantle plumes on the absolute motion change of SA (Fig. 5a,b). Given the relatively low torque-change magnitude required for SA motion change, all plumes are likely to provide sufficient torque change, either by growing or waning in flow strength. This is why all triangles appear large in the figure, as their size reflects the magnitude likelihood. It is important to note that magnitude estimates are strongly dependent on the chosen parameterization. For instance, adopting a lower average asthenosphere viscosity would reduce the reference torque change magnitude (see Section 2.2), thereby increasing the likelihood assigned to any given plume scenario.

When considering the direction of the necessary torque change, the reconstructed slowdown cannot reasonably be attributed to plume

growth (Fig. 5a), as all high likelihood plumes lie behind the Nazca slab, which acts as a geological barrier. When focusing on waning plumes (Fig. 5b), the Saint Helena plume (SH) and a few plume centers across the Atlantic show high orientation-likelihood values. However, the latter plumes lie behind the African Congo Craton, so their influence must be carefully weighted. As a frame of comparison, the simulated Saint Helena plume center has an estimated orientation likelihood of about 70% and a magnitude likelihood of 100%.

For the NZ plate, the slowdown during focus period A is unlikely to have resulted from a strengthening plume, as all plumes with high orientation likelihood are located behind the Nazca slab (Fig. 5c), with the exception of San Felix (SF), which has an orientation likelihood of 45% and a magnitude likelihood of 36%. Waning plumes with moderate joint orientation and magnitude likelihoods (Fig. 5d) include Easter (EA) and to a lesser degree Pitcairn (PC), which have estimated orientation likelihoods of about 32% and 46%, respectively.

3.2. Focus period CB, B and C (~15–10 Ma)

Next, we turn our attention to analyzing the likelihood associated with force changes acting at plates boundaries responsible for the SA absolute motion slowdown during focus period CB (~15–10 Ma, Fig. 6a–d). Orthogonal-inward vectors (Fig. 6a) located between 22°S and 27°S on the NZ–SA boundary can be argued with only 25% confidence. High-likelihood segments for orthogonal-outward vectors (Fig. 6b) are located between latitudes 17°S and 26°S along the SA–NB boundary. All force changes oriented parallel to the relative motion of neighboring NZ can be disregarded with high statistical confidence, due to their near-zero orientation likelihood.

For the NZ plate, we differentiate between focus periods B and C on the basis of the kinematic analysis performed in previous sections.

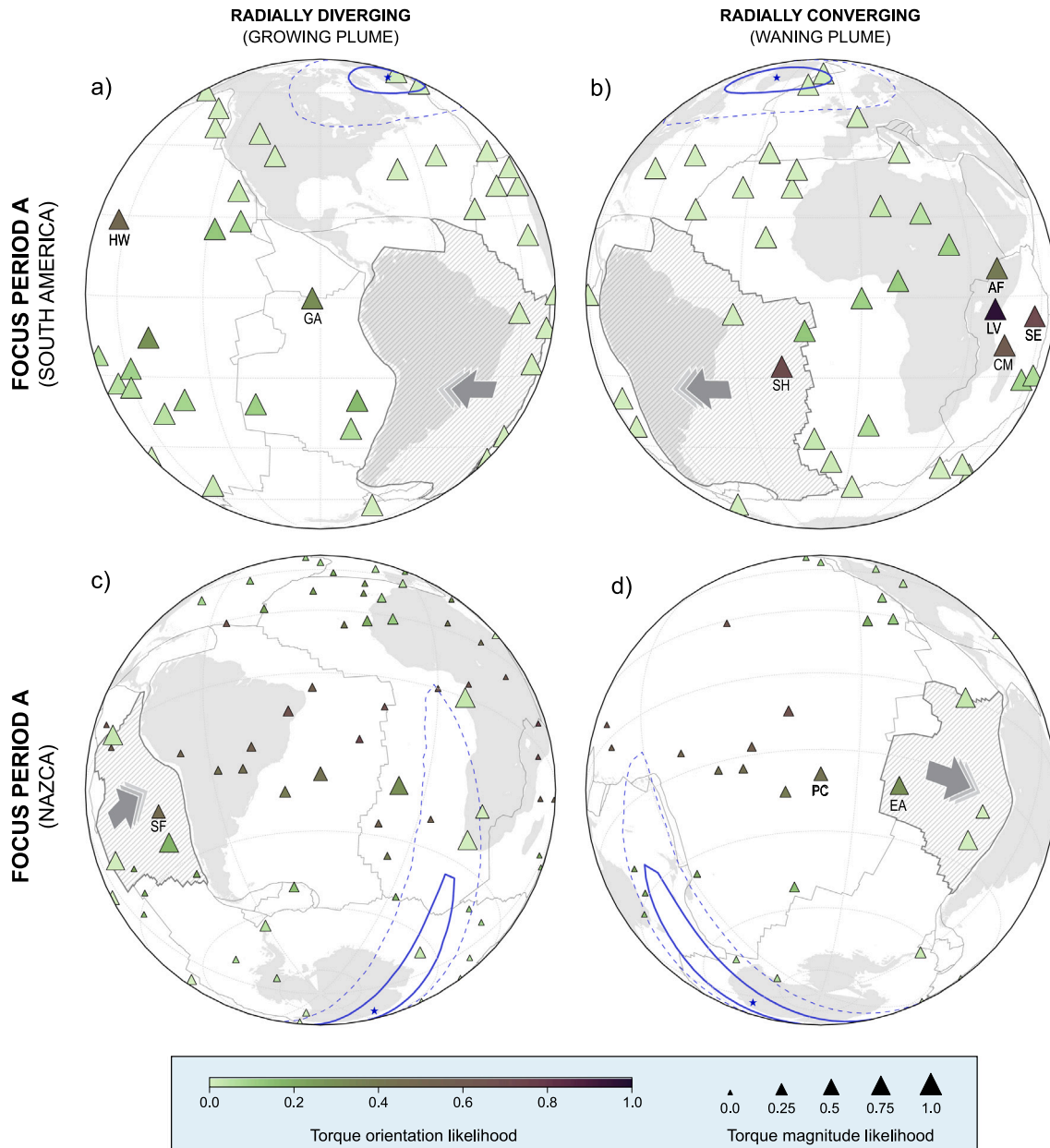


Fig. 5. Probability values indicating how likely the torque changes generated by growing/waning plume-centers around the world are to match the motion-based torque changes during focus period A (~ 9–5 Ma). Colored triangles indicate the position of hotspots as compiled by Whittaker et al. (2015), from which plume force-vector statistics are drawn. The color of the triangles represent the calculated likelihood based on net torque orientation: light green triangles indicate low likelihood values, while dark green/black triangles represent high likelihood values. Triangles increase in size based on net torque magnitude likelihood, assuming a dynamic topography change of 500 m (see main text). Blue star indicates the pole (i.e., direction) of the average motion-based torque-change vector ensembles. Solid, thick blue lines enclose the 68% confidence contours of the ensemble, while dashed, thin blue lines represent the 95% confidence contours. Large gray arrows illustrate the absolute motion change experienced by the plate (see description and legend in Fig. 4). Plume names are shown in black capital letters: AF: Afar, CM: Comores, GA: Galapagos, JF: Juan Fernández, HW: Hawaii, LV: Lake Victoria, PC: Pitcairn, SH: Saint Helena, SE: Seychelles, SF: San Felix, EA: Easter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Focus period B (~12–10 Ma, Fig. 6e–h) displays high-likelihood segments for force-change vectors oriented (i) orthogonal inward (Fig. 6e) along the NZ–PA spreading ridge between latitudes 24°S and 34°S, (ii) orthogonal outward (Fig. 6f) along the NZ–SA trench between latitudes 8°S and 12°S and 19°S and 33°S, and (iii) motion parallel outward (Fig. 6h) between 12°S and 28°S.

For focus period C (~15–12 Ma, Fig. 6i–l), we identify high-likelihood segments for force changes oriented (i) orthogonal inward (Fig. 6i) along the NZ–SA shared boundary between latitudes 9°S and 13°S and (ii) motion-parallel inwards (Fig. 6k) between 9°S and 17°S.

As in Fig. 5, all SA-related plume simulations show high magnitude likelihoods (Fig. 7), reflecting the relatively low torque change required for the reconstructed motion change. However, most plumes also exhibit orientation-likelihood values below 5%, largely due to the narrow confidence contours of the reference torque-change distribution (see blue contours in Fig. 7a,b). Of the plumes tested under flow strengthening scenarios, only Hawaii (HW) exhibits a non-zero orientation likelihood, but its distance from SA and intervening geological barriers make it an unlikely candidate. For the case of waning plumes, those with moderate orientation likelihoods include Lake Victoria (LV, likelihood of 37%), Comores (CM, 30%), and Seychelles (SE, 33%).

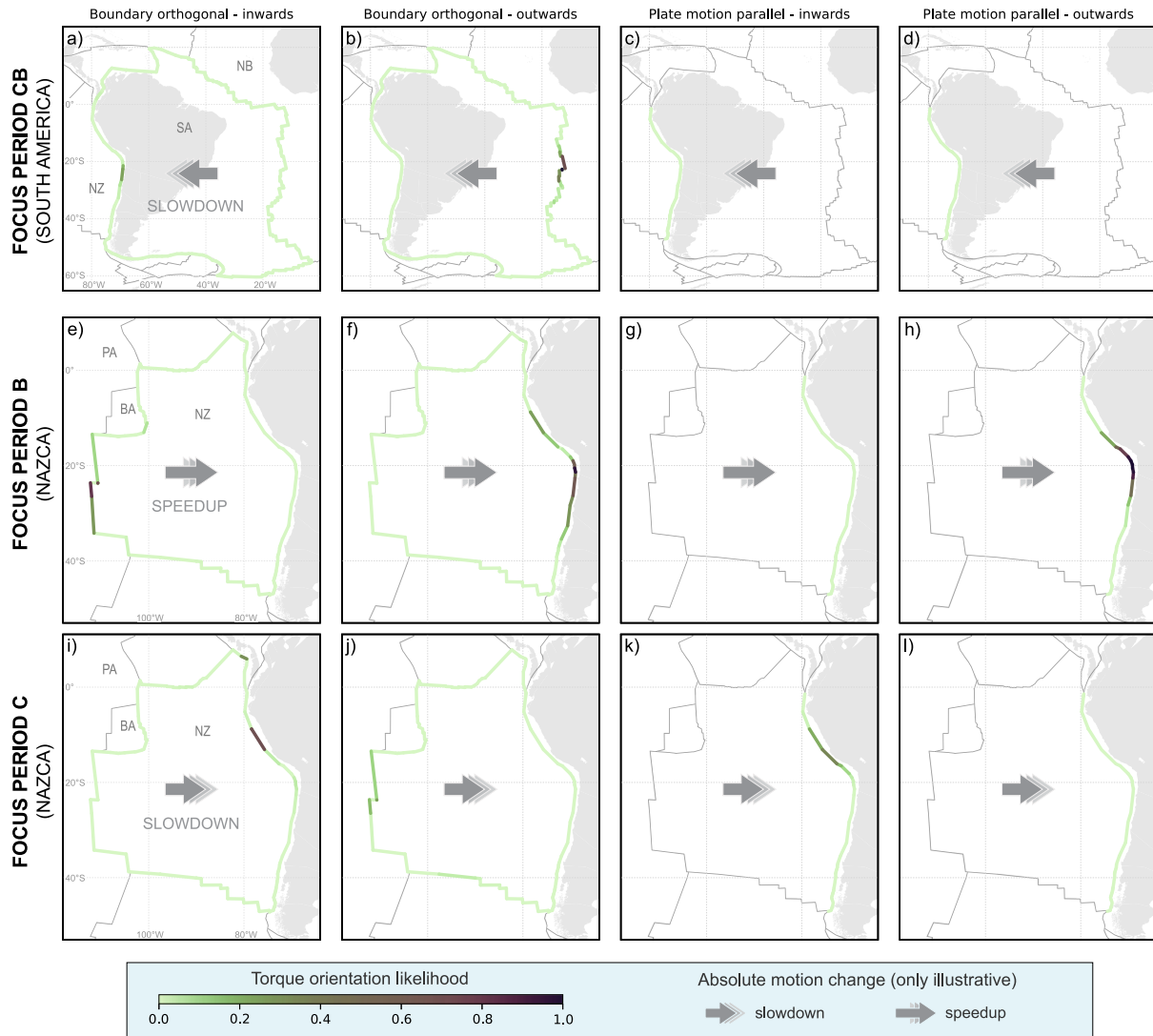


Fig. 6. Same as Fig. 4 but for the combined focus period CB (~15–10 Ma), and the individual focus periods B (~12–10 Ma) and C (~15–12 Ma) (see details in the main text).

Although all of them exhibit magnitude likelihoods above 90%, they are situated behind the African Congo Craton, calling for a careful consideration of their influence.

The reconstructed NZ speedup during focus period B (~12–10 Ma, Fig. 7c,d) coincides with high orientation likelihoods from several plume centers. Among the plumes simulated under flow strengthening scenarios, Easter (EA) displays a 76% likelihood in terms of orientation and a 78% in regards to magnitude. Instead, none of the plumes simulated under flow weakening scenarios shows high likelihood in both orientation and magnitude simultaneously.

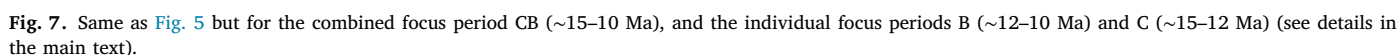
The NZ slowdown observed during focus period C (~15–12 Ma, Fig. 7e,f) could be attributed with high confidence to the directional effect of several plume centers. However, all plume centers for both simulated scenarios yield magnitude likelihoods that are effectively negligible. For reference, the torque variations associated with waning plumes beneath hotspots with high orientation-likelihood values include the Cook Islands (CO, 65%) and Pitcairn (PC, 52%) plumes.

4. Discussion

The likelihood results presented above highlight the force-change vectors most compatible with the reconstructed plate-motion changes. These force changes can arise from diverse geodynamic processes,

with individual processes often capable of affecting multiple forces simultaneously. Quantifying the relative magnitude and interplay of such processes generally requires dedicated numerical modeling and therefore lies beyond the scope of our analytical framework. In the following, our goal is to rather perform a first-order screening of plausible force changes consistent with our probability results, upon which future studies can build using more comprehensive models tailored to, e.g., test specific geodynamic events.

In our analysis, each force change was considered in isolation so that its effect could be evaluated independently. This is a reasonable approach given the short timescales associated with the reconstructed kinematic changes. Nonetheless, NZ and SA share an extensive convergent boundary. Therefore, there is a reasonable possibility that either or both of the following events occur: (i) geological processes occurring along the NZ-SA margin may impact the kinematics of both plates; (ii) a geological process may affect one plate only, but changes in this plate's absolute motion reorient the stresses along the interface with the other plate, thus potentially altering its motion. The degree to which stress reorientation occurs depends predominantly on the extent and degree of rigidity of plate-boundary regions (Gordon, 1998). In any case, we reiterate that rapid kinematic changes must necessarily result from force changes generated by equally-rapid geodynamic events (Iaffaldano and Bunge, 2015).



Mantle drag is the resistive force exerted at the base of tectonic plates as they move. It arises from viscous shearing at the base of the lithosphere and depends on the mantle's viscosity structure (Forsyth

and Uyeda, 1975; Iaffaldano and Bunge, 2015). Because mantle convection operates over long timescales (~ 100 Myr; Bunge et al., 1998), mantle viscosity is not expected to experience drastic changes during the comparatively short periods analyzed in this study. Consequently, mantle drag is unlikely to exert a significant control on short-term plate motion, provided that changes in plate size and geometry remain negligible over the periods considered.

During the Neogene, SA experienced negligible geometric change, whereas NZ underwent a more substantial reshaping linked to the temporary formation and later reincorporation of the Bauer microplate (BA in Fig. 4e), which moved independently between 17 and 6 Ma (Eakins and Lonsdale, 2003). Although its formation predates the periods of interest for this study, its reincorporation falls within the time frame of the slowdown during focus period A (~ 9 –5 Ma). Nevertheless, the contribution of the BA microplate to the mantle drag force is at least an order of magnitude smaller than required to explain NZ slowdown and can therefore be dismissed as a primary driver.

4.1.2. Plume-induced asthenosphere flow changes

Unlike mantle drag, pressure-driven asthenospheric flow can vary on comparatively short timescales and therefore represents a potential driver of rapid plate-motion changes (e.g., Stotz et al., 2018). In this study, we focus on the well-characterized influence of plume upwellings (e.g., Cande and Stegman, 2011; Stotz et al., 2023) and evaluate how their simulated strengthening or waning may account for kinematic changes during our three focus periods.

For focus period A (~ 9 –5 Ma), a waning of the St. Helena (SH) and Easter (EA) plumes produces torque changes that are reasonably compatible – in both orientation and magnitude – with the reconstructed slowdowns of the SA and NZ plates, respectively (see Fig. 5b,d). The Easter plume also yields torque changes capable of accelerating NZ during focus period B (~ 12 –10 Ma), and emerges as the most likely plume-related driver identified in our probabilistic analysis (Fig. 7c).

For the high-likelihood plume centers we investigated potential correlations between our analysis and available geological/geophysical evidence for plume-flow variations. In fact, the St. Helena plume is inferred to have experienced a relatively steady decrease in magma production over the past 30 Ma (Adam et al., 2007). This estimate, however, rests on assumptions such as constant plate motion and may be refined as updated analyses become available. For the Easter plume, no comparable studies have been reported to date, although recent work mapping bathymetric anomalies on the Nazca Plate (e.g., Orozco et al., 2024) provides an important step in that direction. Reconstructed dynamic-topography maps could also offer indirect clues on plume activity, though current inferences are mostly limited to continental regions (e.g., Vilacis et al., 2024). Geological and geophysical data are very limited in the Easter hotspot area; to the best of our knowledge, there are no drilling sites from the International Ocean Discovery Program (IODP) or comparable stratigraphic records in this region. This gap highlights the potential of our method to guide future research efforts.

4.2. Forces acting at the boundaries of plates

4.2.1. Ridge push

Ridge push is controlled by the thermal structure of the oceanic lithosphere at divergent margins (Lister, 1975), and is therefore expected to remain essentially constant per unit length over the short timescales considered here. In principle, the net ridge-push force could change if major plate-boundary reorganizations significantly modified the overall length of divergent margins. As noted above, NZ experienced rapid geometrical changes due to the temporary presence of the BA microplate. However, this breakup geometry produced no appreciable change in the extent of divergent margins for NZ, effectively ruling out ridge push as a significant driver of the reconstructed motion changes.

4.2.2. Slab pull

Slab pull is the driving force arising from the negative buoyancy of subducting slabs (Conrad and Lithgow-Bertelloni, 2002; Schellart, 2004). Although arguably the hardest force to precisely constrain (Iaffaldano and Bunge, 2015), it can generate rapid, significant variations through processes such as slab detachment (Davies and Von Blanckenburg, 1995; Duretz et al., 2012; Garzanti et al., 2018) or the recently proposed slab buckling (Pons et al., 2022; van der Wiel et al., 2024). Slab detachment can produce either positive or negative changes in net slab pull, depending on the post-detachment slab buoyancy relative to the surrounding mantle (Iaffaldano and Bunge, 2015), whereas slab buckling induces cyclical force variations corresponding to forward and backward folding of the slab (van der Wiel et al., 2024).

Because slab pull acts primarily on the subducting plate, these mechanisms may explain the reconstructed NZ speedup during focus period B, as well as the preceding and subsequent slowdowns (focus periods A and C), consistent with the larger torque changes observed in NZ compared to SA. Notably, the duration of each modeled slab buckling cycle (2D modeling in Pons et al., 2022) closely matches the timing of the reconstructed NZ motion changes, suggesting a potential link that could be further explored with full-Earth numerical simulations.

4.2.3. Subduction-interface friction

Changes in the frictional force along the subduction interface are an important driver of variations in the motion of converging plates. Such changes may arise from several geodynamic processes presented in the Introduction, including variations in the friction coefficient, the geometry of the subduction interface, or the gravitational loading associated with mountain uplift. The latter has been identified as a key factor influencing plate motions (e.g., Austermann and Iaffaldano, 2013; Molnar and Stock, 2009; England and Molnar, 2022), and has been specifically cited as a crucial driver of the NZ motion in relation to the uplift of the Andean Cordillera (Iaffaldano et al., 2006; Heidbach et al., 2008). Although typically associated with protracted episodes of motion change (Copley et al., 2010), recent paleoelevation studies of the Andes have revealed episodes of rapid surface uplift linked to lithospheric delamination — the detachment of portions of lower lithosphere (Garzzone et al., 2017; England and Molnar, 2022, and references therein). Torque-change estimates derived from paleotopographic reconstructions (Quiero et al., 2022) fall in the range of 2 to $6 \cdot 10^{25}$ N m, well within the values required by this study (see Table 1).

For the period between ~ 10 and ~ 6 Ma, the main plateau of the Central Andes, known as the Andean Altiplano (17.5°S – 23°S), experienced an estimated uplift of 2.5 ± 1 km (Garzzone et al., 2017). Similarly, the Western Cordillera of southern Peru ($\sim 15^\circ\text{S}$) likely reached its modern elevation of 4.5 km by uplifting 2.2–3.7 km during 19–16 Ma (Saylor and Horton, 2014). During focus periods A (~ 9 –5 Ma) and C (~ 15 –12 Ma), the high-likelihood segments for inward-directed forces coincide with these regions of major uplift (see e.g. Fig. 4a,e). This correspondence is consistent with the force changes expected from mountain building parallel to the convergent margin, supporting a link between the uplift events to the reconstructed NZ/SA slowdowns.

Friction between converging plates may also change in response to the presence of topographic features in the subduction-interphase, such as buoyant ridges or seamount chains (Geersen et al., 2015; Scholz and Small, 1997). While reconstructing such features is beyond the scope of this study, volcanic tracks related to the San Félix hotspot may be extrapolated to coincide with the region highlighted in our results (Fig. 4a,e), representing a promising avenue for future research.

In a final scenario, the reconstructed acceleration of NZ has been associated with enhanced and localized shortening in the overriding SA (Giambiagi et al., 2022, and references therein). Quiero et al. (2022) proposed that this shortening may have been promoted by delamination – i.e., the detachment of the mid-lower crust (Bird, 1979) – of the thickened Andean orogen, which would temporarily reduce the

mechanical strength of the overriding plate through thermal weakening. However, the resulting decrease in plate strength – estimated from a 1D yield-strength envelope (following Giambiagi et al., 2022) applied over a 200 km-long margin segment (from Quiero et al., 2022) – is two orders of magnitude smaller than the torque variation required for the reconstructed NZ speedup. This indicates that delamination alone cannot produce a sufficiently large reduction in the resistance opposing convergence.

By contrast, the required torque change could plausibly arise from a temporary reduction in subduction-interface friction along the same 200 km segment of the margin. In such a scenario, convergence would have been accommodated largely by shortening within SA rather than by subduction during that interval. Typical subduction frictional forces are on the order of $\sim 10^{12}$ N/m (Gurnis et al., 2004), corresponding to $\sim 10^{25}$ N over a 200 km margin – well within the magnitude of torque change needed to explain the reconstructed NZ acceleration.

4.3. Summary per focus period

Based on our methods, the most likely hypotheses concerning the geological processes behind the slowdown and speedup events in NZ and SA are as follows: (i) The slowdowns for both SA (focus period CB) and NZ (focus periods A and C) are well correlated in timing, location and orientation with orogeny-related events (e.g., mountain building, delamination). Magnitude estimates for these events are also compatible with the torque-changes required, as parameterized in this study. We note, however, that this inference is more conclusive for focus period A (~ 9 –5 Ma), where high-likelihood plate-margin segments are prominent and distributed near areas of documented rapid uplift in the Andes. (ii) The NZ speedup during focus period B (~ 12 –10 Ma) has been shown to be consistent with a strengthening of the Easter plume. A more far-fetched hypothesis could involve the compression of SA and consequent speedup of NZ via a reduction of the subduction-interface frictional force. Note that validating these hypotheses with geological observations is beyond the scope of this study, but we hope that the likelihoods provided here can guide future research.

5. Conclusions

In this study, we addressed the interplay between plate-motion changes and geological events capable of inducing those changes with a newly developed methodology. Our case of study was the recent (≤ 20 Ma) episodes of slowdown and speedup affecting the Nazca and South America plates. To do so, we began by reconstructing the Late Neogene absolute motion kinematics of NZ and SA, and estimating the torque variations needed to produce such motion shifts. Using these torque-change estimates as a reference, we assessed how statistically likely are different force changes acting on the margins/base of the plates to produce the reconstructed kinematic changes. These force-change scenarios serve the purpose of simulating the dynamic effects of a broad range of geodynamic processes, including slab pull, subduction friction, or asthenosphere flow change due to nearby plumes. Lastly, we correlated the likelihood values drawn from each force-change scenario with significant geologic events (e.g., mountain building) that occurred in the vicinity of high-likelihood areas.

Our methodology identifies the uplift of the Andes and other related processes as the most likely drivers of the absolute kinematic changes reconstructed for NZ and SA. The contribution of plume-induced flow changes at the base of the plate, under the chosen parameterization, appears to be complementary. Such flow changes could play a more significant role in a different geological scenario, which can be readily assessed using our methodology. Regarding the differences in the torque magnitude required to modify the motions of SA and NZ, which is more prominent during the 15–10 Ma period, we suggest a link to processes related to the NZ subducting slab.

CRediT authorship contribution statement

Valentina Espinoza: Writing – original draft, Visualization, Project administration, Methodology, Formal analysis, Conceptualization. **Juan Martín de Blas:** Writing – original draft, Methodology, Formal analysis. **Ingo L. Stotz:** Writing – original draft, Supervision, Conceptualization. **Andrés Tassara Oddo:** Writing – review & editing, Conceptualization. **Giampiero Iaffaldano:** Writing – original draft, Supervision, Funding acquisition, Formal analysis.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT-4o to improve language and readability. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.tecto.2026.231095>.

Data availability

Noise-mitigated Euler vector datasets, as well as plate-motion change probability distributions were obtained using the software REDBACK (Iaffaldano et al., 2014), available to the public at <http://iearth.edu.au/codes/REDBACK/>. Calculations on finite rotations, Euler vectors and surface velocities were handled using the Julia package, Plate Kinematics v0.2.0 (Espinoza, 2024), available on GitHub at <https://github.com/ValeEspinozaF/PlateKinematics.jl>. Calculations of reference torque changes were performed using the software MYRIAM v1.0.2 (Espinoza et al., 2023). The code used for the remaining analysis and main figures can be downloaded at: <https://doi.org/10.5281/zenodo.17792435>. (Espinoza, 2025).

References

- Adam, C., Vidal, V., Escartín, J., 2007. 80-Myr history of buoyancy and volcanic fluxes along the trails of the Walvis and St. Helena hotspots (South Atlantic). *Earth Planet. Sci. Lett.* 261, 432–442. <http://dx.doi.org/10.1016/j.epsl.2007.07.005>.
- Austermann, J., Iaffaldano, G., 2013. The role of the Zagros orogeny in slowing down Arabia-Eurasia convergence since 5 Ma. *Tectonics* 32, 351–363. <http://dx.doi.org/10.1002/tect.20027>.
- Axen, G.J., Van Wijk, J.W., Currie, C.A., 2018. Basal continental mantle lithosphere displaced by flat-slab subduction. *Nat. Geosci.* 11, 961–964. <http://dx.doi.org/10.1038/s41561-018-0263-9>.
- Bercovici, D., 1995. A source-sink model of the generation of plate tectonics from non-newtonian mantle flow. *J. Geophys. Res.: Solid Earth* 100, 2013–2030. <http://dx.doi.org/10.1029/94JB02598>.
- Bercovici, D., 2003. The generation of plate tectonics from mantle convection. *Earth Planet. Sci. Lett.* 205, 107–121. [http://dx.doi.org/10.1016/S0012-821X\(02\)01009-9](http://dx.doi.org/10.1016/S0012-821X(02)01009-9).
- Bird, P., 1979. Continental delamination and the colorado plateau. *J. Geophys. Res.: Solid Earth* 84, 7561–7571. <http://dx.doi.org/10.1029/JB084iB13p07561>.

- Buffett, B.A., 2006. Plate force due to bending at subduction zones. *J. Geophys. Res.: Solid Earth* 111, <http://dx.doi.org/10.1029/2006JB004295>.
- Bunge, H.P., Richards, M.A., Lithgow-Bertelloni, C., Baumgardner, J.R., Grand, S.P., Romanowicz, B.A., 1998. Time scales and heterogeneous structure in geodynamic earth models. *Science* 280, 91–95. <http://dx.doi.org/10.1126/science.280.5360.91>.
- Cande, S.C., Stegman, D.R., 2011. Indian and african plate motions driven by the push force of the reunion plume head. *Nature* 475, 47–52. <http://dx.doi.org/10.1038/nature10174>.
- Clennett, E.J., Holt, A.F., Tetley, M.G., Becker, T.W., Faccenna, C., 2023. Assessing plate reconstruction models using plate driving force consistency tests. *Sci. Rep.* 13, 10191. <http://dx.doi.org/10.1038/s41598-023-37117-w>.
- Colli, L., Stotz, I., Bunge, H.P., Smethurst, M., Clark, S., Iaffaldano, G., Tassara, A., Guillocheau, F., Bianchi, M.C., 2014. Rapid south atlantic spreading changes and coeval vertical motion in surrounding continents: Evidence for temporal changes of pressure-driven upper mantle flow. *Tectonics* 33, 1304–1321. <http://dx.doi.org/10.1002/2014TC003612>.
- Conrad, C.P., Lithgow-Bertelloni, C., 2002. How mantle slabs drive plate tectonics. *Science* 298, 207–209. <http://dx.doi.org/10.1126/science.1074161>.
- Conrad, C.P., Lithgow-Bertelloni, C., 2004. The temporal evolution of plate driving forces: Importance of “slab suction” versus “slab pull” during the cenozoic. *J. Geophys. Res.: Solid Earth* 109, <http://dx.doi.org/10.1029/2004JB002991>.
- Copley, A., Avouac, J.P., Royer, J.Y., 2010. India-Asia collision and the cenozoic slowdown of the Indian plate: Implications for the forces driving plate motions. *J. Geophys. Res.: Solid Earth* 115, <http://dx.doi.org/10.1029/2009JB006634>.
- Cox, A., Hart, R.B., 1986. *Plate Tectonics: How It Works*. Blackwell Scientific Publications, Palo Alto.
- Croon, M.B., Cande, S.C., Stock, J.M., 2008. Revised Pacific-Antarctic plate motions and geophysics of the Menard Fracture Zone. *Geochem. Geophys. Geosystems* 9, <http://dx.doi.org/10.1029/2008GC002019>.
- Davies, J.H., Von Blanckenburg, F., 1995. Slab breakoff: A model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens. *Earth Planet. Sci. Lett.* 129, 85–102. [http://dx.doi.org/10.1016/0012-821X\(94\)00237-S](http://dx.doi.org/10.1016/0012-821X(94)00237-S).
- DeMets, C., Merkouriev, S., 2019. High-resolution reconstructions of South America plate motion relative to Africa, Antarctica and North America: 34 Ma to present. *Geophys. J. Int.* 217, 1821–1853. <http://dx.doi.org/10.1093/gji/ggz087>.
- Dominguez, S., Lallemand, S., Malavieille, J., Von Huene, R., 1998. Upper plate deformation associated with seamount subduction. *Tectonophysics* 293, 207–224. [http://dx.doi.org/10.1016/S0040-1951\(98\)00086-9](http://dx.doi.org/10.1016/S0040-1951(98)00086-9).
- Dobrovine, P.V., Steinberger, B., Torsvik, T.H., 2012. Absolute plate motions in a reference frame defined by moving hot spots in the Pacific, Atlantic, and Indian oceans. *J. Geophys. Res.: Solid Earth* 117, <http://dx.doi.org/10.1029/2011JB009072>.
- Duretz, J., Schmalholz, S., Gerya, T., 2012. Dynamics of slab detachment. *Geochem. Geophys. Geosystems* 13, <http://dx.doi.org/10.1029/2011GC004024>.
- Eakins, B.W., Lonsdale, P.F., 2003. Structural patterns and tectonic history of the bauer microplate, Eastern Tropical Pacific. *Mar. Geophys. Res.* 24, 171–205. <http://dx.doi.org/10.1007/s11001-004-5882-4>.
- England, P., Molnar, P., 2022. Changes in plate motions caused by increases in gravitational potential energy of mountain belts. *Geochem. Geophys. Geosystems* 23, <http://dx.doi.org/10.1029/2022GC010389>, e2022GC010389.
- Espinoza, V., 2024. Valeespinoza/platekinematics.jl: v0.2.0. <http://dx.doi.org/10.5281/zenodo.12773819>.
- Espinoza, V., 2025. Data and code for “plate motion drivers: Geodynamical framework and statistical appraisal for the case of the neogene nazca - South America convergence”. <http://dx.doi.org/10.5281/zenodo.17792435>.
- Espinoza, V., Martin de Blas, J., Iaffaldano, G., 2023. Myriam. <http://dx.doi.org/10.5281/zenodo.10447863>.
- Espinoza, V., Martin de Blas, J., Iaffaldano, G., 2024. MYRIAM: Open-source software to estimate torque variations associated with plate-motion temporal changes. *Geochem. Geophys. Geosystems* 25, <http://dx.doi.org/10.1029/2023GC011095>, e2023GC011095.
- Espinoza, V., Iaffaldano, G., 2023. Rapid absolute plate motion changes inferred from high-resolution relative spreading reconstructions: A case study focusing on the South America plate and its Atlantic/Pacific neighbors. *Earth Planet. Sci. Lett.* 604, 118009. <http://dx.doi.org/10.1016/j.epsl.2023.118009>.
- Faccenna, C., Becker, T.W., Lallemand, S., Steinberger, B., 2012. On the role of slab pull in the cenozoic motion of the pacific plate. *Geophys. Res. Lett.* 39, <http://dx.doi.org/10.1029/2011GL050155>.
- Forsyth, D., Uyeda, S., 1975. On the relative importance of the driving forces of plate motion. *Geophys. J. Int.* 43, 163–200. <http://dx.doi.org/10.1111/j.1365-246X.1975.tb00631.x>.
- Garzanti, E., Radef, G., Malusà, M.G., 2018. Slab breakoff: A critical appraisal of a geological theory as applied in space and time. *Earth-Sci. Rev.* 177, 303–319. <http://dx.doi.org/10.1016/j.earscirev.2017.11.012>.
- Garzone, C.N., McQuarrie, N., Perez, N.D., Ehlers, T.A., Beck, S.L., Kar, N., Eichelberger, N., Chapman, A.D., Ward, K.M., Ducea, M.N., Lease, R.O., Poulsen, C.J., Wagner, L.S., Saylor, J.E., Zandt, G., Horton, B.K., 2017. Tectonic evolution of the central andean plateau and implications for the growth of plateaus. *Annu. Rev. Earth Planet. Sci.* 45, 529–559. <http://dx.doi.org/10.1146/annurev-earth-063016-020612>.
- Geersen, J., Ranero, C.R., Barckhausen, U., Reichert, C., 2015. Subducting seamounts control interplate coupling and seismic rupture in the 2014 iquique earthquake area. *Nat. Commun.* 6, 8267. <http://dx.doi.org/10.1038/ncomms9267>.
- Giambiagi, L., Tassara, A., Echaurren, A., Julve, J., Quiroga, R., Barrionuevo, M., Liu, S., Echeverría, I., Mardónez, D., Suriano, J., et al., 2022. Crustal anatomy and evolution of a subduction-related orogenic system: Insights from the Southern Central Andes (22–35 S). *Earth-Sci. Rev.* 232, 104138. <http://dx.doi.org/10.1016/j.earscirev.2022.104138>.
- Gordon, R.G., 1998. The plate tectonic approximation: Plate nonrigidity, diffuse plate boundaries, and global plate reconstructions. *Annu. Rev. Earth Planet. Sci.* 26, 615–642. <http://dx.doi.org/10.1146/annurev.earth.26.1.615>.
- Gurnis, M., Hall, C., Lavier, L., 2004. Evolving force balance during incipient subduction. *Geochem. Geophys. Geosystems* 5, <http://dx.doi.org/10.1029/2003GC000681>.
- Hartley, R.A., Roberts, G.G., White, N., Richardson, C., 2011. Transient convective uplift of an ancient buried landscape. *Nat. Geosci.* 4, 562–565. <http://dx.doi.org/10.1038/ngeo1191>.
- Heidbach, O., Iaffaldano, G., Bunge, H.P., 2008. Topography growth drives stress rotations in the central Andes: Observations and models. *Geophys. Res. Lett.* 35, <http://dx.doi.org/10.1029/2007GL032782>.
- Hoggard, M., White, N., Al-Attar, D., 2016. Global dynamic topography observations reveal limited influence of large-scale mantle flow. *Nat. Geosci.* 9, 456–463. <http://dx.doi.org/10.1038/ngeo2709>.
- Höink, T., Jellinek, A.M., Lenardic, A., 2011. Viscous coupling at the lithosphere-asthenosphere boundary. *Geochem. Geophys. Geosystems* 12, <http://dx.doi.org/10.1029/2011GC003698>.
- Höink, T., Lenardic, A., 2008. Three-dimensional mantle convection simulations with a low-viscosity asthenosphere and the relationship between heat flow and the horizontal length scale of convection. *Geophys. Res. Lett.* 35, <http://dx.doi.org/10.1029/2008GL033854>.
- Höink, T., Lenardic, A., 2010. Long wavelength convection, poiseuille-couette flow in the low-viscosity asthenosphere and the strength of plate margins. *Geophys. J. Int.* 180, 23–33. <http://dx.doi.org/10.1111/j.1365-246X.2009.04404.x>.
- Hu, J., Gurnis, M., Rudi, J., Stadler, G., Müller, R.D., 2022. Dynamics of the abrupt change in Pacific plate motion around 50 million years ago. *Nat. Geosci.* 15, 74–78. <http://dx.doi.org/10.1038/s41561-021-00862-6>.
- Hu, J., Liu, L., Gurnis, M., 2021. Southward expanding plate coupling due to variation in sediment subduction as a cause of andean growth. *Nat. Commun.* 12, 7271. <http://dx.doi.org/10.1038/s41467-021-27518-8>.
- Iaffaldano, G., Bunge, H.P., 2015. Rapid plate motion variations through geological time: Observations serving geodynamic interpretation. *Annu. Rev. Earth Planet. Sci.* 43, 571–592. <http://dx.doi.org/10.1146/annurev-earth-060614-105117>.
- Iaffaldano, G., Bunge, H.P., Dixon, T.H., 2006. Feedback between mountain belt growth and plate convergence. *Geology* 34, 893–896. <http://dx.doi.org/10.1130/G22661.1>.
- Iaffaldano, G., Davies, D.R., DeMets, C., 2018. Indian ocean floor deformation induced by the reunion plume rather than the tibetan plateau. *Nat. Geosci.* 11, 362–366. <http://dx.doi.org/10.1038/s41561-018-0110-z>.
- Iaffaldano, G., DeMets, C., 2016. Late Neogene changes in North America and Antarctica absolute plate motions inferred from the Mid-Atlantic and Southwest Indian Ridges spreading histories. *Geophys. Res. Lett.* 43, 8466–8472. <http://dx.doi.org/10.1002/2016GL070276>.
- Iaffaldano, G., Hawkins, R., Bodin, T., Sambridge, M., 2014. REDBACK: Open-source software for efficient noise-reduction in plate kinematic reconstructions. *Geochem. Geophys. Geosystems* 15, 1663–1670. <http://dx.doi.org/10.1002/2014GC005309>.
- Jagoutz, O., Royden, L., Holt, A.F., Becker, T.W., 2015. Anomalously fast convergence of India and Eurasia caused by double subduction. *Nat. Geosci.* 8, 475–478. <http://dx.doi.org/10.1038/ngeo2418>.
- Knesel, K.M., Cohen, B.E., Vasconcelos, P.M., Thiede, D.S., 2008. Rapid change in drift of the Australian plate records collision with Ontong Java plateau. *Nature* 454, 754–757. <http://dx.doi.org/10.1038/nature07138>.
- Li, K., Hu, J., Li, Y., Zhou, H., Zhang, H., 2024. Slab segmentation and stacking in mantle transition zone controls disparate surface and lower mantle subducting rates and complex slab morphology. *Geophys. Res. Lett.* 51, <http://dx.doi.org/10.1029/2024GL110202>, e2024GL110202. <https://doi.org/10.1029/2024GL110202>.
- Lister, C.R.B., 1975. Gravitational drive on oceanic plates caused by thermal contraction. *Nature* 257, 663–665. <http://dx.doi.org/10.1038/257663a0>.
- Lithgow-Bertelloni, C., 2016. Driving forces: Slab pull, ridge push. In: *Encyclopedia of Marine Geosciences*. Springer, pp. 193–196. http://dx.doi.org/10.1007/978-94-007-6238-1_105.
- Lithgow-Bertelloni, C., Richards, M.A., 1995. Cenozoic plate driving forces. *Geophys. Res. Lett.* 22, 1317–1320. <http://dx.doi.org/10.1029/95GL01325>.
- Mardia, K.V., Jupp, P.E., 2009. *Directional Statistics*. John Wiley & Sons.
- Martin de Blas, Juan, Iaffaldano, Giampiero, 2019. Using rigid microplate motions to detect the stress buildup preceding large earthquakes: A feasibility test based on synthetic models. *J. Geophys. Res.: Solid Earth* 124, 13468–13485. <http://dx.doi.org/10.1029/2019JB018175>.
- Matthews, K.J., Maloney, K.T., Zahirovic, S., Williams, S.E., Seton, M., Müller, R.D., 2016. Global plate boundary evolution and kinematics since the late Paleozoic. *Glob. Planet. Change* 146, 226–250. <http://dx.doi.org/10.1016/j.gloplacha.2016.10.002>.

- Mitrovica, J.X., 1996. Haskell [1935] revisited. *J. Geophys. Res.: Solid Earth* 101, 555–569. <http://dx.doi.org/10.1029/95JB03208>.
- Molnar, P., Stock, J.M., 2009. Slowing of India's convergence with Eurasia since 20 Ma and its implications for Tibetan mantle dynamics. *Tectonics* 28, <http://dx.doi.org/10.1029/2008TC002271>.
- Ogg, J., 2020. Geomagnetic polarity time scale. In: *Geologic Time Scale 2020*. Elsevier, pp. 159–192. <http://dx.doi.org/10.1016/B978-0-12-824360-2.00005-X>.
- Orozco, G., Lara, L.E., Tassara, A., 2024. Characterization and geodynamic interpretation of nazca plate bathymetric anomalies. *Earth Planet. Sci. Lett.* 647, 119009. <http://dx.doi.org/10.1016/j.epsl.2024.119009>.
- Paulson, A., Richards, M.A., 2009. On the resolution of radial viscosity structure in modelling long-wavelength postglacial rebound data. *Geophys. J. Int.* 179, 1516–1526. <http://dx.doi.org/10.1111/j.1365-246X.2009.04362.x>.
- Phipps Morgan, J., Morgan, W.J., Zhang, Y.S., Smith, W.H., 1995. Observational hints for a plume-fed, suboceanic asthenosphere and its role in mantle convection. *J. Geophys. Res.: Solid Earth* 100, 12753–12767. <http://dx.doi.org/10.1029/95JB00041>.
- Pons, M., Sobolev, S.V., Liu, S., Neuhaerth, D., 2022. Hindered trench migration due to slab steepening controls the formation of the Central Andes. *J. Geophys. Res.: Solid Earth* 127, <http://dx.doi.org/10.1029/2022JB025229>, e2022JB025229.
- Priestley, K., McKenzie, D., 2013. The relationship between shear wave velocity, temperature, attenuation and viscosity in the shallow part of the mantle. *Earth Planet. Sci. Lett.* 381, 78–91. <http://dx.doi.org/10.1016/j.epsl.2013.08.022>.
- Quiro, F., Tassara, A., Iaffaldano, G., Rabbia, O., 2022. Growth of Neogene Andes linked to changes in plate convergence using high-resolution kinematic models. *Nat. Commun.* 13, 1339. <http://dx.doi.org/10.1038/s41467-022-29055-4>.
- Ratnaswamy, V., Stadler, G., Gurnis, M., 2015. Adjoint-based estimation of plate coupling in a non-linear mantle flow model: theory and examples. *Geophys. J. Int.* 202, 768–786. <http://dx.doi.org/10.1093/gji/ggv166>.
- Rosenbaum, G., Giles, D., Saxon, M., Betts, P.G., Weinberg, R.F., Duboz, C., 2005. Subduction of the Nazca Ridge and the Inca Plateau: Insights into the formation of ore deposits in Peru. *Earth Planet. Sci. Lett.* 239, 18–32. <http://dx.doi.org/10.1016/j.epsl.2005.08.003>.
- Saylor, J.E., Horton, B.K., 2014. Nonuniform surface uplift of the Andean plateau revealed by deuterium isotopes in Miocene volcanic glass from Southern Peru. *Earth Planet. Sci. Lett.* 387, 120–131. <http://dx.doi.org/10.1016/j.epsl.2013.11.015>.
- Schellart, W.P., 2004. Quantifying the net slab pull force as a driving mechanism for plate tectonics. *Geophys. Res. Lett.* 31, L07611. <http://dx.doi.org/10.1029/2004GL019528>.
- Scholz, C.H., Small, C., 1997. The effect of seamount subduction on seismic coupling. *Geology* 25, 487–490. [http://dx.doi.org/10.1130/0091-7613\(1997\)025<0487:TEOSSO>2.3.CO;2](http://dx.doi.org/10.1130/0091-7613(1997)025<0487:TEOSSO>2.3.CO;2).
- Stadler, G., Gurnis, M., Burstedde, C., Wilcox, L.C., Alisc, L., Ghattas, O., 2010. The dynamics of plate tectonics and mantle flow: From local to global scales. *Science* 329, 1033–1038. <http://dx.doi.org/10.1126/science.1191223>.
- Stotz, I.L., Iaffaldano, G., Davies, D.R., 2018. Pressure-driven poiseuille flow: A major component of the torque-balance governing Pacific plate motion. *Geophys. Res. Lett.* 45, 117–125. <http://dx.doi.org/10.1002/2017GL075697>.
- Stotz, I.L., Vilacis, B., Hayek, J.N., Bunge, H.P., Friedrich, A.M., 2021. Yellowstone plume drives neogene North American plate motion change. *Geophys. Res. Lett.* 48, <http://dx.doi.org/10.1029/2021GL095079>, e2021GL095079.
- Stotz, I.L., Vilacis, B., Hayek, J.N., Carena, S., Bunge, H.P., 2023. Plume driven plate motion changes: New insights from the South Atlantic realm. *J. South Am. Earth Sci.* 124, 104257. <http://dx.doi.org/10.1016/j.jsames.2023.104257>.
- Suchoy, L., Goes, S., Chen, F., Davies, D.R., 2022. How aseismic ridges modify the dynamics of free subduction: A 3-d numerical investigation. *Front. Earth Sci.* 10, 852742. <http://dx.doi.org/10.3389/feart.2022.852742>.
- Tackley, P.J., 1998. Self-consistent generation of tectonic plates in three-dimensional mantle convection. *Earth Planet. Sci. Lett.* 157, 9–22. [http://dx.doi.org/10.1016/S0012-821X\(98\)00029-6](http://dx.doi.org/10.1016/S0012-821X(98)00029-6).
- Tebbens, S., Cande, S., Kovacs, L., Parra, J., LaBrecque, J., Vergara, H., 1997. The Chile ridge: A tectonic framework. *J. Geophys. Res.: Solid Earth* 102, 12035–12059. <http://dx.doi.org/10.1029/96JB02581>.
- Vilacis, B., Brown, H., Bunge, H.P., Carena, S., Hayek, J., Stotz, I., Wang, Z., Friedrich, A., 2024. Dynamic topography and the planform of mantle convection since the Jurassic inferred from global continental hiatus maps. In: *Proceedings A. The Royal Society*, 20240311. <http://dx.doi.org/10.1098/rspa.2024.0311>.
- Vilacis, B., Hayek, J.N., Stotz, I.L., Bunge, H.P., Friedrich, A.M., Carena, S., Clark, S., 2022. Evidence for active upper mantle flow in the Atlantic and Indo-Australian realms since the Upper Jurassic from hiatus maps and spreading rate changes. *Proc. R. Soc. A* 478, 20210764. <http://dx.doi.org/10.1098/rspa.2021.0764>.
- Wang, Z.R., Iaffaldano, G., Hopper, J.R., 2024. Changes of North Atlantic plate motion in early Paleogene driven by Icelandic plume: Insights from kinematic and stratigraphic constraints. *Earth Planet. Sci. Lett.* 641, 118831. <http://dx.doi.org/10.1016/j.epsl.2024.118831>.
- Wessel, P., Kroenke, L.W., 2000. Ontong Java Plateau and late Neogene changes in Pacific plate motion. *J. Geophys. Res.: Solid Earth* 105, 28255–28277. <http://dx.doi.org/10.1029/2000JB900290>.
- Wessel, P., Kroenke, L.W., 2008. Pacific absolute plate motion since 145 Ma: An assessment of the fixed hot spot hypothesis. *J. Geophys. Res.: Solid Earth* 113, <http://dx.doi.org/10.1029/2007JB005499>.
- Whittaker, J., Afonso, J., Masterton, S., Müller, R., Wessel, P., Williams, S., Seton, M., 2015. Long-term interaction between mid-ocean ridges and mantle plumes. *Nat. Geosci.* 8, 479–483. <http://dx.doi.org/10.1038/ngeo2437>.
- van der Wiel, E., Pokorný, J., Čížková, H., Spakman, W., van den Berg, A.P., van Hinsbergen, D.J., 2024. Slab buckling as a driver for rapid oscillations in Indian plate motion and subduction rate. *Commun. Earth Environ.* 5, 316. <http://dx.doi.org/10.1038/s43247-024-01472-x>.
- Zhou, H., Hu, J., Dal Zilio, L., Tang, M., Li, K., Hu, X., 2024. India–Eurasia convergence speed-up by passive-margin sediment subduction. *Nature* 635, 114–120. <http://dx.doi.org/10.1038/s41586-024-08069-6>.