Towards a Solid Earth Integrated Reference Frame

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Key Points:

- We construct a minimum continent velocity mantle reference frame and quantify uncertainty.
- Other parameters of plate-mantle interaction are coupled through the absolute plate model.
- This Solid Earth Integrated Reference Frame allows coupled hypothesis testing, reconstructing relative motions in the mantle, and training numerical models.

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Abstract

Studying mantle convection requires knowledge of how plates moved over and subduct into the mantle. Therefore, relative plate tectonic reconstructions are placed in a mantle reference frame. These use the geological expressions of plate-mantle interactions and correlate these to mantle structure or minimize plate motions that would cause friction with the mantle under the null hypothesis that active horizontal flow in the mantle is negligible. However, mantle reference frames based on different plate-mantle interactions are different. This may be due to model uncertainty, but may also hold meaningful geophysical signals. To explore this, we first computed a reference frame, in 10 Ma steps, that adheres to a 'tectonic rule' that minimizes absolute total continent motion. We estimate the uncertainty by assigning a ± 5 Ma time window to the 10 Ma intervals and find that the continent frame, or alternative frames based on an alternative 'rules', may provide meaningful results for the last 350 Ma, but are unresolved before that time. With this base frame, we predict hotspot trails, kimberlite and large igneous provinces eruption sites, net lithosphere rotation, trench kinematics, and true polar wander, which are all mostly within plausible ranges. We introduce this coupled frame as a Solid Earth Integrated Reference Frame (SEIRF) that may be used (1) to aid interpretation of anomalous geodynamic behavior; (2) to obtain novel constraints on mantle convection - the SEIRF allows studying 'mantle kinematics' in a plate tectonic reference frame and (3) may serve to train 3D numerical models of solid Earth dynamics.

Plain Language Summary

We observe the expressions of solid Earth dynamics at the Earth's surface in the form of hotspot trails, trench kinematics, plate velocity, net lithosphere rotation, true polar wander, and kimberlite and large igneous province eruptions. We may compute these parameters given the absolute motion of plates relative to the mantle, but finding true absolute plate motion, as well as true horizontal motion of the mantle remains a challenge. Here, we approximate absolute plate motion relative to the mantle by assuming minimal continent velocity. The resulting mantle reference frame holds a prediction for all expressions of plate-mantle interaction, which we dub the Solid Earth Integrated Reference Frame (SEIRF). We show that by coupling all parameters within one frame, we learn about solid Earth dynamics even without knowing true absolute plate motion. For instance, we may investigate anomalous behavior in one parameter and see if the anomaly fits with other parameters or exists in isolation. Moreover, with the SEIRF, we may investigate relative motions between mantle sources of e.g. hotspots and kimberlites, which are independent of the absolute plate model. The SEIRF allows training of numerical models of solid Earth dynamics with all independent observations of mantle behavior.

1 Introduction

The clearest expression of Earth's unique mode of mantle convection is plate tectonics. Since the development of the theory of plate tectonics (McKenzie, 1969), plate reconstructions have been used as basis to decipher the relative motions within the mantle, and between plates and the mantle, for instance using hotspot trails (e.g. Burke and Wilson (1976)). This led to the development of 'mantle reference frames' that describe the 'absolute' movement of tectonic plates relative to the mantle (e.g. Cox and Hart (1991)) Such frames (e.g. Duncan (1981); Müller et al. (1993); Duncan and Richards (1991); Le Pichon et al. (2019); Torsvik, Burke, et al. (2010); Torsvik et al. (2006); Burke and Torsvik (2004)) implicitly take as null hypothesis that active horizontal flow in the ambient mantle is negligible. Such reference frames are then used as basis to interrogate the null-hypothesis, for instance, by analyzing how mantle flow may move hotspots relative to each other (Doubrovine et al., 2012), how slabs may sink through the mantle (van der Meer et al., 2010), how

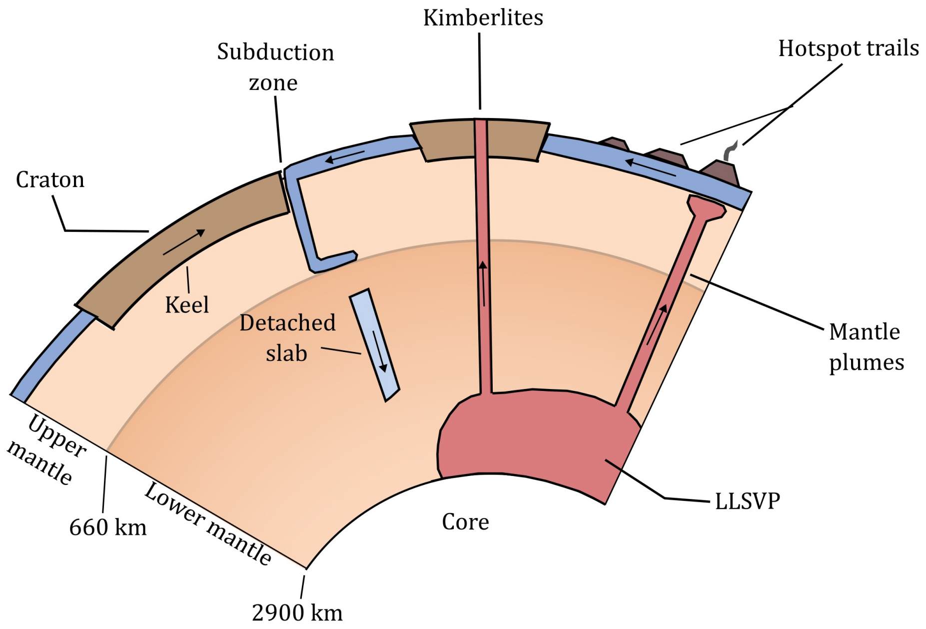

Figure 1. Schematic cross section of the mantle showing selected plate-mantle interactions. The black arrows indicate motion. LLSVP: Large Low Shear Velocity Province.

changes in Earth's moment of inertia rotate the solid Earth relative to the spin axis (e.g. (Steinberger & Torsvik, 2010)), or how rheological differences in the upper mantle may lead to net lithosphere rotation (Conrad & Behn, 2010; Gérault et al., 2012). These and many other processes within the mantle, or between mantle and lithosphere, are underpinned by independent geological and geophysical observations that led to many different mantle reference frames. What is encouraging is that all frames predict similar behavior in terms of rates of absolute plate motions or subduction zone behavior, despite being noticeably different (Becker et al., 2015; Torsvik et al., 2008; Williams et al., 2015; Müller et al., 2022).

On the one hand, the differences between mantle reference frames may represent uncertainties and noise. Under that assumption Tetley et al. (2019) recently introduced a Tectonic Rules Model (TRM) that aimed to average differences. The TRM is a mathematical method that considers the observed kinematic surface expression of different plate-mantle interactions ("tectonic rules") and assigns each an (arbitrary) weighting to compute an average ('optimal') absolute plate motion frame. On the other hand, the differences may hold a meaningful geophysical signal that provides a unique way to constrain how, where, and when motions in the mantle occurred. In that case, the different mantle reference frames should not be averaged, but the differences between should be quantified and studied. Here, we use the TRMs ability to build mantle reference frames from plate kinematic observations to explore that alternative possibility.

In this paper, we first calculate a mantle reference frame using one selected plate-mantle interaction as a base model. To this end, we choose one of the 'rules' of the TRM of Tetley et al. (2019), namely minimizing absolute continental plate motions, under the null hypothesis that ambient horizontal upper mantle flow is negligable. We then estimate uncertainty in this TRM frame, evaluating the effect of errors and uncertainties in the plate circuit propagating back in time. Next, we compute the difference with other observables of plate-mantle interaction and mantle convection (Figure 1). These include trench migration, net lithosphere rotation, hotspot motion, eruption locations of large igneous provinces and kimberlites, and true polar wander. This way, we aim to provide a next step towards creating an internally coherent, integrated set of kinematic constraints that include relative plate motions and relative mantle motions as constraint on solid Earth dynamics. Finally, we will discuss how these coupled properties aid in analyzing geological observations that may challenge the current status quo, how it may constrain mantle kinematics, and how it may contribute to training the next generation of 3D geodynamic numerical models.

2 Approach

2.1 Base model: continent frame

We use the TRM to optimize fit to one kinematic expression of plate-mantle interaction and determine misfit with other kinematic parameters. The original TRM (Tetley et al., 2019) included three "tectonic rules": minimizing hotspot misfit, minimizing absolute trench migration, and limiting net lithospheric rotation to a chosen maximum value, and was expanded to four "tectonic rules" with minimizing continent velocity in (Müller et al., 2022). These were then fitted simultaneously by weighting each model equally. Following Müller et al. (2022), we use the relative plate model of Merdith et al. (2021) as basis.

For practical reasons, we chose a 'continent frame' as base frame that can be computed with only a relative plate model as input. The continent frame assumes that plates that carry continents have deep keels into the upper mantle, which anchor the plate to the ambient mantle and resist absolute continent motion to minimize friction (Forsyth & Uyeda, 1975; Zahirovic et al., 2015). Motions of continents, which are tectonic features that may remain stable for hundreds of millions of years, are the best-constrained features in plate tectonic reconstructions. To build the continent frame, we construct a TRM that minimizes mean global velocity of continents. The TRM generates a 1^o grid covering the Earth's surface and for each grid point determines the velocity vector. If a grid point exists within the continental polygons defined by Merdith et al. (2021), the velocity magnitude is included in the mean velocity. This method ensures the velocity of plates is weighted according to the area of continental crust they contain in the computation of the mean global continent velocity. The resulting mean velocity is minimized in a chosen, fixed time interval (here 10 Ma, in contrast to 5 Ma in Müller et al. (2022)). We slightly deviate from the TRM of Müller et al. (2022) by using the mean instead of the median global continental plate velocity. In absence of the other tectonic rules, using the median causes the TRM to keep any continental block exceeding 50% of all continental surface area fixed to obtain a zero median. Using the mean global continental plate velocity eliminates this artefact.

Evidently, any relative plate motion model that underpins the computation of a continent frame contains uncertainties and errors. Uncertainties in the positions of continents in plate models at a given reconstruction time stem for a large part from age uncertainties in the underlying data, such as in the dating of marine magnetic anomalies or the initiation and cessation of rifts and subduction zones. To evaluate possible effects of such age errors, we ran the TRM for the base frame ca. 180 times, each iteration drawing a new age range where each timestep is randomly selected from a 10 ± 5 Ma window. For example, rather than a sequence of ages such as 10,20, and 30 Ma, a random draw may produce a sequence such as 7,19, and 32 Ma. The optimal pole reconstructing Africa relative to the mantle for each time window is collected per iteration and we calculate an uncertainty ellipse encompassing 95% of the poles using the Kent distribution (Kent, 1982).

2.2 Coupled properties

Next, we use the base model and the associated uncertainty to calculate (mis)fits to other plate-mantle interactions, as well as to the Earth's magnetic field. These include (1) trench kinematics, (2) hotspots; (3) net lithosphere rotation; (4) kimberlite and large igneous province eruption sites relative to seismologically imaged deep-mantle structure; and (5) a paleomagnetic reference frame. Misfits with the base model may then result from (a) errors in the relative plate circuit, underestimation of base model uncertainty, or an invalid assumption underlying the base model, or (b) a meaningful geophysical signal of mantle dynamics.

2.2.1 Trench kinematics

An alternative mantle reference frame that seeks to minimize friction of tectonic plates with the underlying mantle is the 'trench frame', which assumes that the ambient mantle resists lateral motion of subducting slabs (Schellart et al., 2007, 2008; Spakman et al., 2018; Lallemand et al., 2005). In principle, a trench frame may therefore also be used as an alternative base model, as it builds on the same underlying assumption as the continent frame, and it was included in the TRM of Tetley et al. (2019); Müller et al. (2022). However, uncertainty in reconstructing subduction zones is much larger than uncertainty in reconstructing continents. Subduction zones are transient features and they may move relative to overriding plates, causing orogenic deformation and back-arc extension at plate margins, which needs to be included in the plate reconstruction (Müller et al., 2019; van Hinsbergen et al., 2011, 2020; van Hinsbergen & Schmid, 2012). This means that age uncertainty associated with the appearance and disappearance of a subduction zone, as well as with its position relative to stable plate interiors as a result of orogenic deformation comes on top of the uncertainty in rotations of the relative plate model, which makes it difficult to quantify. If the overriding plate is continental, remnants of ancient subduction zones are better preserved in the geological record and may be taken into account in plate reconstructions (e.g. van Hinsbergen et al. (2011)). Preservation of geological records of intra-oceanic subduction zones is poorer and although reconstruction is possible (Boschman et al., 2021; Stampfli & Borel, 2002; Clennett et al., 2020; Vaes et al., 2019; van de Lagemaat et al., 2024)), uncertainty is large. To illustrate, we computed a trench frame using the relative plate model of Merdith et al. (2021), but we note that even for Mesozoic and Cenozoic time, considerably different interpretations of intra-oceanic subduction are available. For instance, the Merdith et al. (2021) model contains few intra-oceanic subduction zones in the Pacific realm, whereas recent reconstructions offer solutions with tens of thousands of kilometers of intra-oceanic trenches (e.g. Vaes et al. (2019); Clennett et al. (2020); van de Lagemaat et al. (2024)). In addition, Merdith et al. (2021) contains a major intra-oceanic subduction zone within the eastern Neotethys ocean known as the conceptual 'Trans-Tethyan arc' that advances rapidly in the late Cretaceous Cenozoic (Martin et al., 2020), whereas alternative views offer solutions without such a trench (Advokaat & van Hinsbergen, 2024). It is beyond the scope of this paper to show how such differences may impact the predicted trench kinematics, or a minimum trench motion base frame, but they may strongly influence e.g. maximum rates of trench motion. In this paper, we take the reconstruction of Merdith et al. (2021) at face value to evaluate how robust reference frames based on minimizing friction may be. For this construction of the trench frame we use the global mean of absolute orthogonal trench migration, which is computed with

$$TM = \frac{\sum |V_t|}{T_n} \tag{1}$$

where $|V_t|$ is the absolute magnitude of the trench-orthogonal velocity vector for each trench segment, and T_n is the number of trench segments.

In addition, trench kinematics are an intrinsic feature of any absolute plate model and hold information on the dynamic interaction of individual slabs with the mantle they subduct into. For present-day subduction zones, patterns of trench behavior are extensively studied (Schellart et al., 2008; Lallemand et al., 2005; Williams et al., 2015; Faccenna et al., 2007; Spakman et al., 2018; van de Lagemaat et al., 2018). Deviations of trench kinematics in the continent frame from these patterns may thus invite scrutiny of the plate reconstruction, or may signal atypical slab-mantle interaction. We therefore compute the global mean and maximum trench retreat and advance rates, as well as the mean and maximum trench-parallel slab dragging rates.

2.2.2 Hotspot misfit

Hotspot trails form by the progressive formation of volcanoes and are in their simplest form the result of a plate moving over a fixed mantle source, generally thought to represent a mantle plume (Wilson, 1963; Morgan, 1972; Duncan, 1981; Duncan & Richards, 1991; Müller et al., 1993). Reconstructions of hotspot trails show that hotspot sources (plumes) may move slowly (<1 cm/yr) relative to each other (Steinberger, 2000; Tarduno & Cottrell, 1997; Doubrovine et al., 2012; O'Neill et al., 2005), although plume migration rate of up to 4 cm/yr has also been suggested (Tarduno et al., 2003), and plume-lithosphere interaction may be remarkably long-lived (Torsvik et al., 2013; Rojas-Agramonte et al., 2022). Any absolute plate motion model comes with a unique set of predicted hotspot motions. We illustrate this by determining the predicted hotspot misfit and associated required hotspot source motion for the base models using a selection of four long-lasting hotspot trails: Hawaii and Louisville in the Pacific Ocean, Tristan in the Atlantic Ocean and Reunion in the Indian Ocean. We computed the great-circle distance of each dated point in these hotspot trails to the projected location in the base frames using the Haversine equation

$$d = 2r\sin^{-1}\left(\sqrt{\left(\frac{\phi_2-\phi_1}{2}\right) + \cos(\phi_1)\cos(\phi_2)\sin^2\left(\frac{\lambda_2-\lambda_1}{2}\right)}\right) \tag{2}$$

where d is the great-circle distance, r is the radius of the Earth, ϕ_1 and ϕ_2 are the latitude of the two points in radians, and λ_1 and λ_2 are the longitude of the two points in radians. In case of a misfit, we compute the predicted absolute motion of the hotspot source. We interpolate the projected locations of the plume to 10 Ma intervals and compute the misfit taking into account the uncertainty of the base model and the age uncertainty of the dated hotspots and seamounts.

2.2.3 Net lithospheric rotation

Any absolute plate motion model comes with a unique value for net lithosphere rotation. Net lithosphere rotation is calculated by summing all surface velocity vectors on a grid and integrating the result over the surface of the Earth (Solomon et al., 1975; Torsvik, Steinberger, et al., 2010). A non-zero value means that the lithosphere experiences a net rotation relative to the underlying non-lithospheric mantle. Such a net rotation may result from artifacts, such as uncertainty or oversimplification in the plate reconstruction (Torsvik, Steinberger, et al., 2010), but may also hold a meaningful geophysical signal. A non-zero value of net rotation may result from lateral viscosity differences at the plate-mantle interface that may cause variations in coupling of the lithosphere to the asthenosphere and thus variations in the resistance of plates to plate motion (Conrad & Behn, 2010; Becker, 2008; Atkins & Coltice, 2021; Gérault et al., 2012). Estimates of such coupling for the present-day are inferred from seismic anisotropy (Becker, 2008). Values of 0.2-0.3^o/Ma are deemed reasonable from geodynamic modelling (Conrad & Behn, 2010). Higher numbers even up to 1.0^o/Ma may signal anomalously low plate-mantle coupling, e.g. due to reduced upper mantle viscosity and a spike in velocity of a particular plate

(Atkins & Coltice, 2021; Gérault et al., 2012), but also invite scrutinizing the relative and absolute plate motion model (Torsvik, Steinberger, et al., 2010).

We calculate net rotation following the method described in Torsvik, Steinberger, et al. (2010) (Equation 3) using the optimal interval of 5 Ma as suggested in Atkins and Coltice (2021).

$$\omega_{net} = 3/(8\pi r^4) \int v \times RdS = 3/(8\pi r^4) \sum_i \int (\omega_i \times R) \times RdS_i \tag{3}$$

where ω_{net} is the NLR rate in degrees per million years,r is the radius of the Earth, v is the velocity vector, R is the position vector, ω_i is the angular velocity vector of plate i, $\int ...dS$ indicates integration over the entire sphere, $\sum_i$ indicates summation over all plates, and $\int ...dS_i$ indicates integration over the area of plate i.

2.2.4 Kimberlite and LIPs versus LLSVP margins

Burke and Torsvik (2004) found a correlation between the positions of modern deep-seated hotspots and the edges of the modern Large Low Shearwave Velocity Provinces (LLSVPs) at the core-mantle boundary as imaged in seismic tomography. In addition, they showed that when reconstructed in a hotspot mantle reference frame, also large igneous provinces (LIPs) appear to have formed above these edges (see also Torsvik et al. (2006); Burke et al. (2008)). These correlations were used to suggest that plumes are generated along the edges of LLSVPs (the 'plume generation zones' of Burke et al. (2008)). Later, Torsvik, Burke, et al. (2010) found that also kimberlites, which are thought to result from interactions of mantle plumes with cratonic mantle lithosphere, fit such a pattern, scattered in a zone of ˜10^o around the margins of the modern LLSVPs. From this correlation it follows that prediction of the absolute eruption location of LIPs and kimberlites invites scrutiny of their relation to the LLSVP margins through time. The predicted eruption locations are directly coupled to the mantle reference frame and may form another constraint on a successful mantle model. For instance, if the eruption locations would systematically shift, this could indicate either absolute motion of the LLSVP margins (as suggested by e.g. Bodur and Flament (2023)), or horizontal motions in the plume conduit (analogous to hotspot drift, e.g. Steinberger (2000)), or errors in the mantle reference frame or plate reconstruction. Therefore, we include the predicted eruptions locations of LIPs and kimberlites into the SEIRF.

To this end, we used the LIP database of Burke and Torsvik (2004) and the kimberlite database of Torsvik, Burke, et al. (2010), for the last 350 Ma. Note that Torsvik, Burke, et al. (2010) identified a cluster of outlying kimberlites in North America that did not erupt above the edges of the LLSVPs. We have omitted these data, so that the pattern of kimberlite eruption locations predicted by our base models may be compared to the pattern predicted by Torsvik, Burke, et al. (2010) based on their absolute reference frames (based on the hybrid reference frame of Torsvik et al. (2008)).

2.2.5 True polar wander

True Polar Wander (TPW) is the rotation of the solid Earth relative to the spin axis that results from changes in the moment of inertia (Goldreich & Toomre, 1969). Earth's moment of inertia may change due to motions of density anomalies through the mantle, particularly subducting slabs (Steinberger & Torsvik, 2010). LLSVPs, which are centered around the equator (Garnero, 2000) are thought to have a stabilizing effect on TPW (Steinberger & Torsvik, 2010). Moreover, the effect of subducting slabs on TPW is opposite in the upper and lower mantle, such that the TPW oscillates and the net effect is zero (Steinberger & Torsvik, 2010; Steinberger et al., 2017). TPW is straightforwardly determined from the angular difference between a mantle reference frame and a paleomagnetic reference frame and has previously been computed using hotspot frames for the time period for which hotspot data is available (e.g. Livermore et al. (1984); Besse and Courtillot (2002); Doubrovine et al. (2012)). TPW computation for older times relies on determining the common rotation of a plate circuit within a paleomagnetic frame (Steinberger & Torsvik, 2008). Recent computations of TPW thereby assumed that TPW in the past occurred around the same axis that corresponds to the modern moment of inertia (0, 11^o E), which is in the center of the LLSVP (Torsvik et al., 2014). Importantly, this requires assumptions on the absolute paleolongitude of the plate circuit which is paleomagnetically unconstrained (Torsvik et al., 2014). Moreover, TPW as recent as the Cenozoic occurred along an axis that was almost orthogonal to 0, 11 ^{o} E (Doubrovine et al., 2012) (Vaes & van Hinsbergen, 2024). Strong deviations from previously computed TPW values thus either require changes in the absolute paleolongitude of the plate circuit through time, or variation of the axis of TPW, which are intrinsically related to variations in Earth's moment of inertia and the stabilizing role of the LLSVPs therein. This forms an important potential source of information of solid Earth dynamics (Vaes & van Hinsbergen, 2024). Therefore, we compute a prediction of TPW that follows from our base frame by computing a TPW path by placing the global APWP of Vaes et al. (2023) in our base mantle frame.

3 Results

3.1 Base frame: predicted motion path of Africa and uncertainty estimates

We used the reconstruction of Merdith et al. (2021) that provides a plate model back to 1 Ga, to compute a continent frame (Table 1), and for comparison a trench frame, in 10 Ma steps for the entire duration of the model. We then estimated the uncertainty as outlined in the previous section, and determined how far back in time the absolute plate motion in 10 Ma steps tends to exceed the uncertainty. We show the resulting absolute plate motion paths in coordinates of Africa, for a location in the center of the African continent (2°S, 16°E) (Figures 2a and 2b).

The trajectories of the two motion paths are at first order similar. Back to 120 Ma, the continent frame computed migration of the African plate in a general NE direction. While Pangea and further back Gondwana are unified, from ca. 570 Ma to 120 Ma, Africa is kept fixed in place. In the period before the formation of Gondwana, between 570-620 Ma, the African plate is moved to the SW. This is preceded by a S-N loop between 620-860 Ma following the break-up of Rodinia at ca. 860 Ma. From 1000-860 Ma, the central African craton as part of Rodinia is once again kept fixed. The trench frame does move Pangea in a E-W loop between ~120-400 Ma. The general W direction is maintained while the African plate is part of Gondwana, with three N-S oscillations in the path. The absolute movement of the African plate in the trench frame before the formation of Gondwana is roughly similar, although Rodinia is not kept as much in place.

Table 1. Total reconstruction poles of the absolute motion of the African plate in the Continent frame.

Time (Ma)	Latitude	Longitude	Angle
10	20.15	-26.68	-1.21
20	19.21	-23.06	-2.35
30	26.90	-21.40	-4.45
40	-29.63	158.45	7.06
50	-31.77	157.41	9.43
60	-32.56	154.42	10.66
70	-33.06	155.04	12.14
80	-34.39	156.94	15.66
90	35.29	-20.94	-20.16
100	35.40	-20.82	-25.56
110	34.92	-19.71	-31.16
120	33.50	-18.01	-37.14
130	32.36	-16.88	-39.59
140	31.24	-16.82	-41.29
150	30.65	-16.97	-42.16
160	29.67	-16.48	-43.31
170	28.79	-15.58	-44.75
180	28.51	-14.79	-45.31
190	28.42	-14.07	-45.67
200	28.34	-13.37	-46.00
210	28.32	-13.34	-46.02
220	28.32	-13.34	-46.02
230	28.32	-13.34	-46.02
240	28.32	-13.34	-46.02
250	28.32	-13.34	-46.02
260	28.32	-13.34	-46.02
270	28.32	-13.34	-46.02
280	-28.32	166.66	46.02
290	-28.32	166.66	46.02
300	-28.32	166.66	46.02
310	-28.32	166.66	46.02
320	-28.32	166.66	46.02
330	-28.32	166.66	46.02
340	-28.32	166.66	46.02
350	-28.32	166.66	46.02

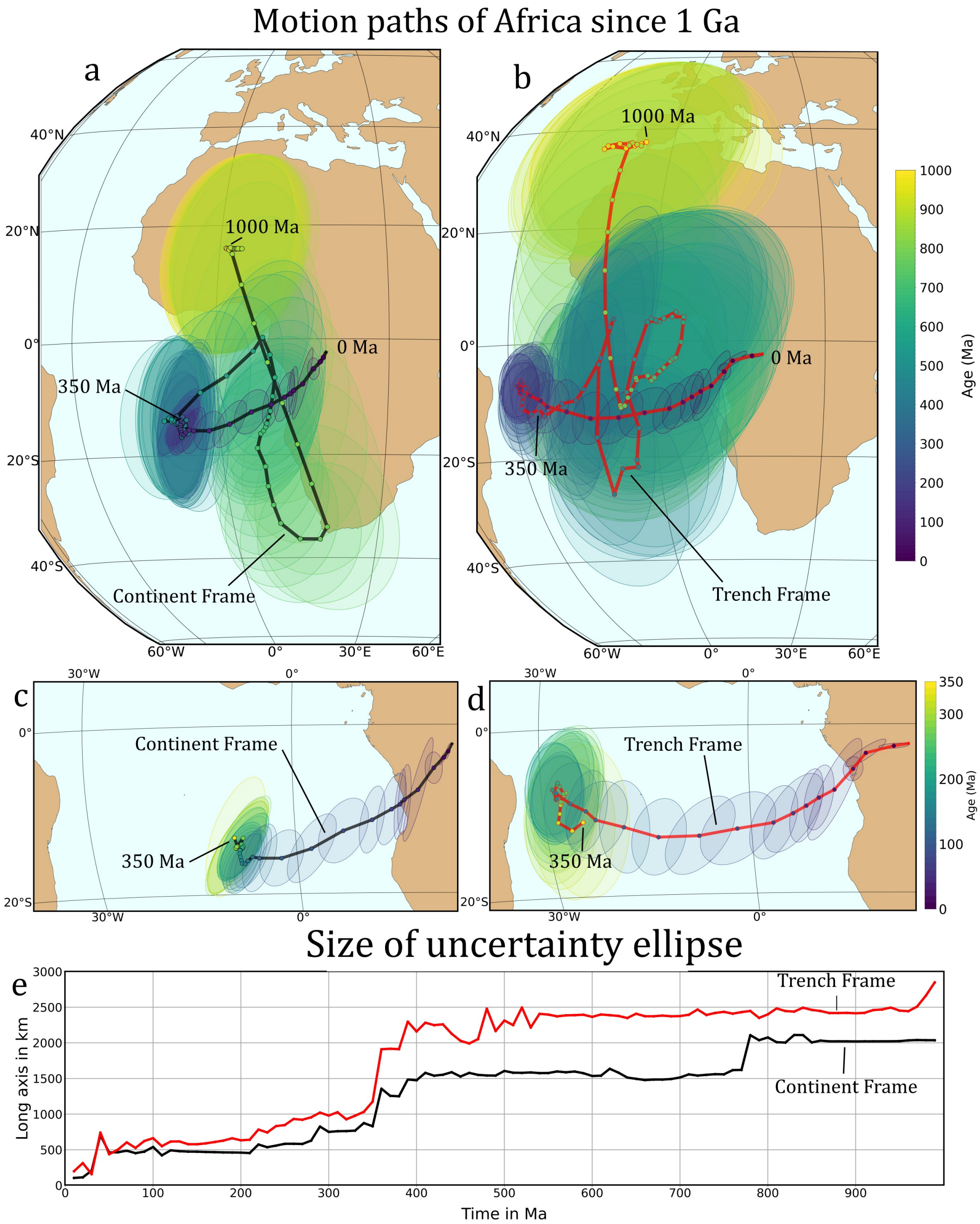

Figure 2. Motion paths from 1000-0 Ma of an arbitrary point in Central Africa in the continent (a) and trench (b) frames. The motion path is computed in 10 Ma time intervals with a ±5 Ma window that results in an uncertainty ellipse encompassing 2σ of all points. Subfigures (c) and (d) show the motion paths of Africa since 350 Ma for the continent and trench frame respectively. (e) The length of the long axis of the uncertainty ellipse over time for the continent frame (black) and trench frame (red).

The uncertainty estimates that follow from our 180 iterations varying the age window increases throughout time for both the continent frame and the trench frame (Figure 2e). The length of the long axis of the uncertainty ellipse in the continent frame rises

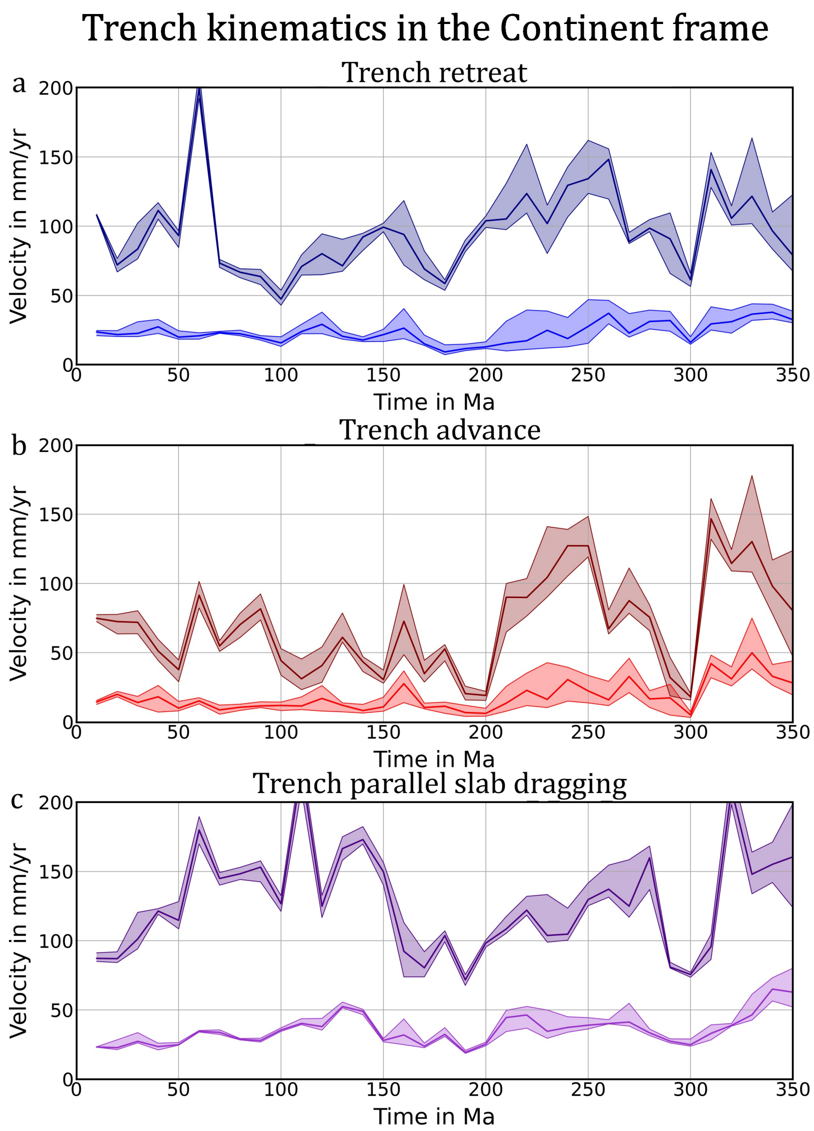

Figure 3. Trench kinematics as computed in the continent frame. (a) Orthogonal trench retreat, (b) orthogonal trench advance, (c) parallel slab dragging. The lighter shade represents the global mean value and the darker shade the maximum value computed for one trench segment. The schematic drawings on the right show how trench retreat is computed as the absolute orthogonal motion of the trench towards the subducting plate, how trench advance is computed as the absolute orthogonal motion of the trench towards the overriding plate, and how parallel slab dragging is computed as the absolute parallel motion of the subducting plate along the trench.

sharply back in time at 350 Ma and ˜780 Ma. These moments coincide with the formation of the supercontinents Pangea and Rodinia, in which major continents move in unison. The time periods before these supercontinents are associated with more complex modeled continent motions that are less well constrained and motion changes are more abrupt. The long axis of the uncertainty ellipse in the trench frame increases more than the continent frame at 350 Ma. Prior to 350 Ma, uncertainty ellipses in most cases encompass the magnitude of absolute plate motion when calculated in 10 Ma intervals. Absolute plate motions estimated with the TRM approach prior to 350 Ma in 10 Ma intervals as used by Tetley et al. (2019) and in this paper, and especially in 5 Ma intervals as in Müller et al. (2022), are thus unconstrained. In the following sections, we therefore focus on the time window of 350-0 Ma (Figures 2c and d).

3.2 Coupled properties

We now explore how the coupled properties behave in the base frame, for which we chose the continent frame.

3.2.1 Trench kinematics

Our base frame predicts values for the mean orthogonal trench retreat and trench advance rates that are on the order of 2-5 cm/yr for times after ~200 Ma (Figure 3a and b respectively). This is within the range computed for the present day (Schellart et al., 2008). Trench-parallel slab dragging rates are in the same range (Figure 3c), which compares well with reconstructed examples (van de Lagemaat et al., 2018; Parsons et al., 2021), although no global means have so far been computed. The computed values for the maximum rates are high and contain sharp spikes, which may indicate errors in the plate model or narrow trenches obeying motions of large surrounding plates. Prior to 200 Ma, the maximum value for trench advance rises to 10-15 cm/yr, which is caused by rapid trench migration of reconstructed narrow trenches in the Tethys Oceans in the relative plate model of Merdith et al. (2021).

3.2.2 Hotspot trails

We may now use our base model to predict hotspot trails assuming hotspot fixity. The four hotspot trails that we selected in the Pacific (Hawai'i-Emperor, Louisville), Atlantic (Tristan), and Indian oceans (Reunion) overall fit the predicted trails, although deviations are obvious (Figure 4). We infer from this that the base frame may represent a reasonable starting point towards an absolute plate motion frame. The description below of apparent hotspot source motion should thus not be taken as an interpretation of geological history, but as an illustration of how constraints from hotspots may be used in a SEIRF.

The Hawai'i-Emperor hotspot trail, which in previous moving hotspot models and in numerical experiments is often hypothesized to be among the fastest moving ones (Doubrovine et al., 2012; Hassan et al., 2016), as well as from paleomagnetic data (Tarduno et al., 2003). Interestingly, our base frame predicts the Hawai'i-Emperor hotspot trail, including its marked kink around 45-50 Ma, surprisingly well assuming hotspot fixity (Figure 4a). If our base model would be correct, it would predict some hotspot motion, because the predicted trail lags slightly behind the observed trail, i.e. our Pacific plate moves in the right direction but either the plate is too slow or the hotspot source moved slowly. Some southward absolute hotspot source motion is barely larger than the uncertainty ellipses (Figure 4e). Also for the Louisville hotspot, the continent frame predicts the real trail remarkably well (Figure 4b) and the hotspot source would within error be nearly fixed relative to the mantle (Figure 4f).

The base frame predicts the last 60 Ma of the Reunion trail, located on the African/Somalian plate well (Figure 4c), with no more than about 2^o of hotspot source migration since that time (Figure 4g). Finally, for the Tristan hotspot, the base frame predicts the hotspot trail well for the last 60 Ma, whereas between 130-60 Ma the predicted trail and reference trail deviate increasingly back in time (Figure 4d). Accordingly, the predicted plume migration is practically zero for 0-60 Ma, while between 130-60 Ma, the hotspot source is predicted to migrate ca. 13^o in a fairly continuous motion to the southeast (Figure 4h).

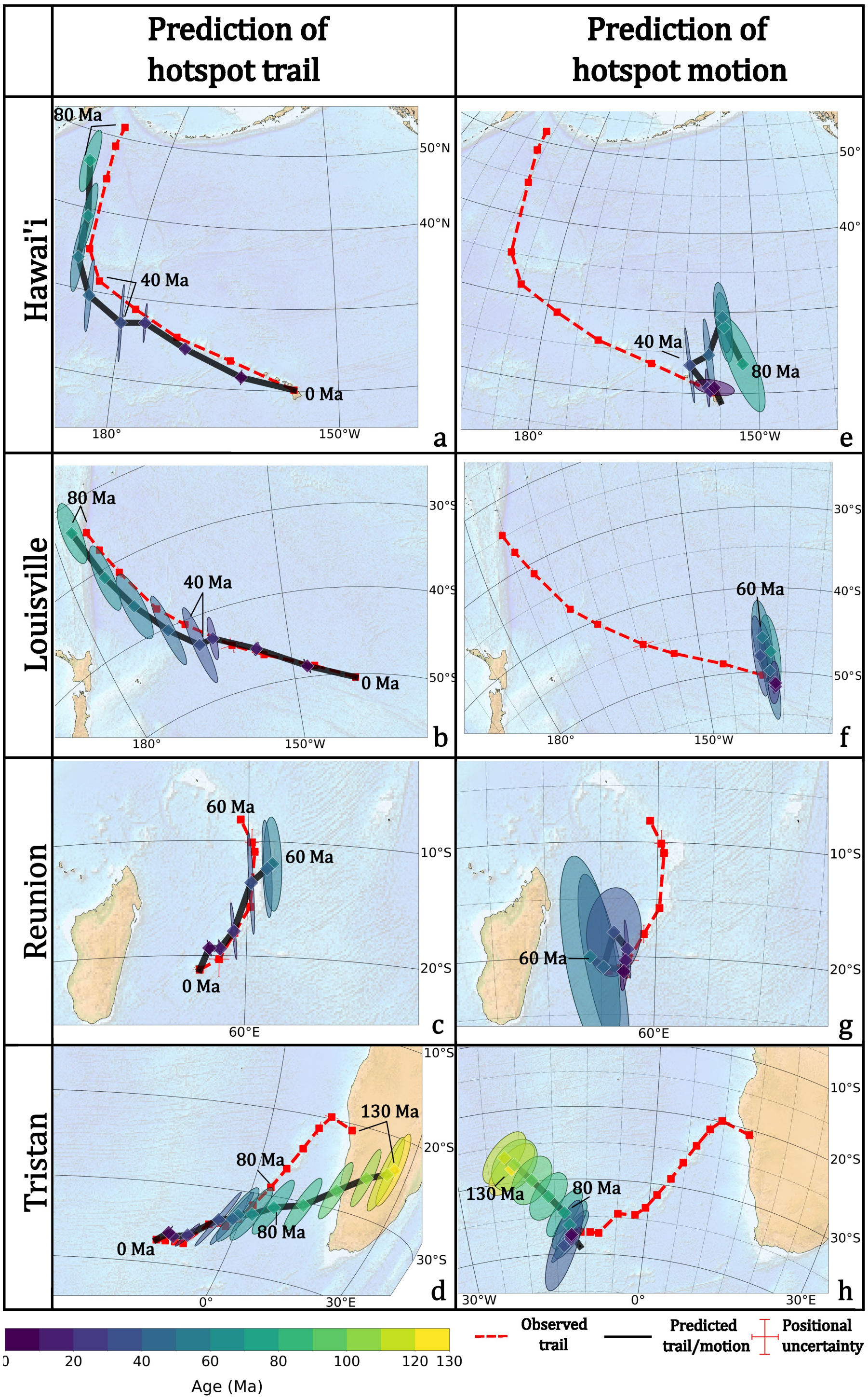

Figure 4. The prediction of selected hotspot trails in the continent frame. The black line represents the predicted trail or the predicted hotspot source motion in the continent frame and the black dashed path represents the observed trail. The predicted trails and source motion are calculated to 10 Ma time intervals. Each point includes an uncertainty ellipse from the age uncertainty estimate, which are colored according to time. The reference trails are interpolated to 10 Ma intervals and include the positional uncertainty arising from the age uncertainty of the volcanic islands and seamounts, which is marked with red error bars.

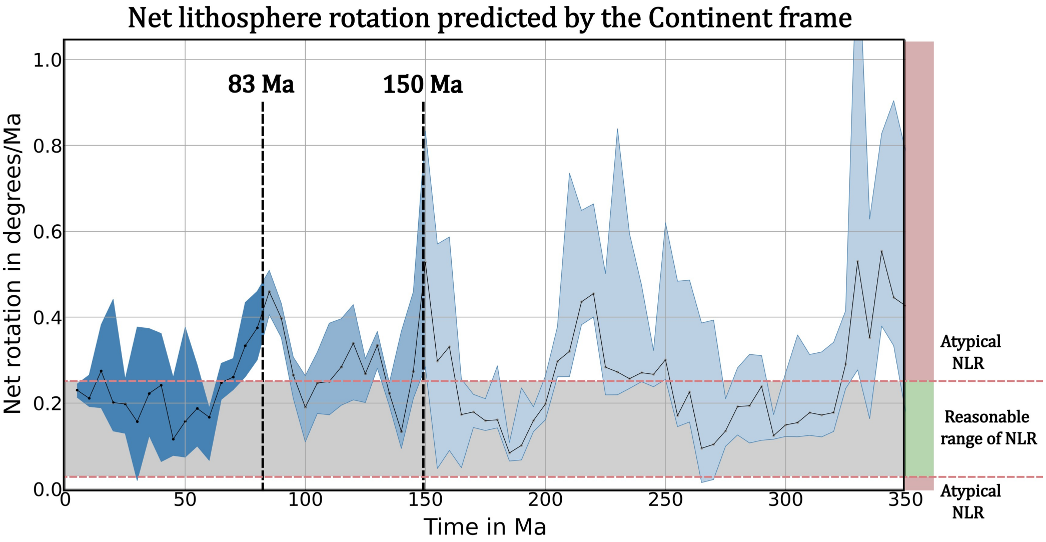

Figure 5. Predicted net lithospheric rotation in the base frame, correlated over 5 Ma time intervals. The red dashed line shows the maximum expected value for net rotation from geodynamic modelling (Becker, 2008; Conrad & Behn, 2010). The time period prior to 83 and 150 Ma is marked and faded out, to indicate the diminished robustness of the net rotation computation due to losing the plate tectonic connections to the plates in the Pacific realm.

3.2.3 Net lithosphere rotation

For much of the last 350 Ma, the computed net rotation values lie within the 0-0.3^o/Ma range that is within the range for the present day (Becker, 2008; Conrad & Behn, 2010), although there are notable peaks (Figure 5). A period of higher net rotation occurs between 75-95 Ma, peaking at 0.5^o/Ma at 85 Ma. These values stem from the reconstruction of very high velocity (>20 cm/yr) of a fast-moving plate in the NW paleo-Pacific realm (Izanagi plate) in this time (Merdith et al., 2021; Lin et al., 2022). If such peaks are the result of lateral viscosity contrasts in the upper mantle, they hold interesting geodynamic information. However, they may also result from errors in the plate reconstruction, whereby oceanic plates - having large surface areas and high velocities - have a large influence. Prior to 83 Ma, the connection of the Pacific plates to the Indo-Atlantic plates through Antarctica is lost, adding considerable uncertainty (Doubrovine & Tarduno, 2008). Prior to 150 Ma, hotspot control on Pacific plate motion is absent (Torsvik & Cocks, 2019) and interpretation of oceanic plates and intra-oceanic subduction zones in the Panthalassa Ocean differs strongly between authors (Merdith et al., 2021; Boschman et al., 2021; van de Lagemaat et al., 2023; Lin et al., 2022). It is therefore challenging to straightforwardly identify plate modelling artefacts from true net rotation before 83 Ma.

3.2.4 Kimberlite and LIPs reconstruction

Our base frame predicts the locations of kimberlites and LIPs at time of eruption relative to the edges of the present-day LLSVPs. Kimberlites and LIPs for the last 350 Ma cluster on the edges of LLSVPs (Figure 6). In addition, the predicted motions of the Indo-Atlantic hotspots occur more or less along the edges of the African LLSVP (Figure 6). What stands out is a notable eastward shift in kimberlite and LIP sources in the Atlantic realm during the Cretaceous, ˜120-80 Ma. This shift would mean that kimberlite sources in southern Africa reconstructed above the outer edge of the modern African

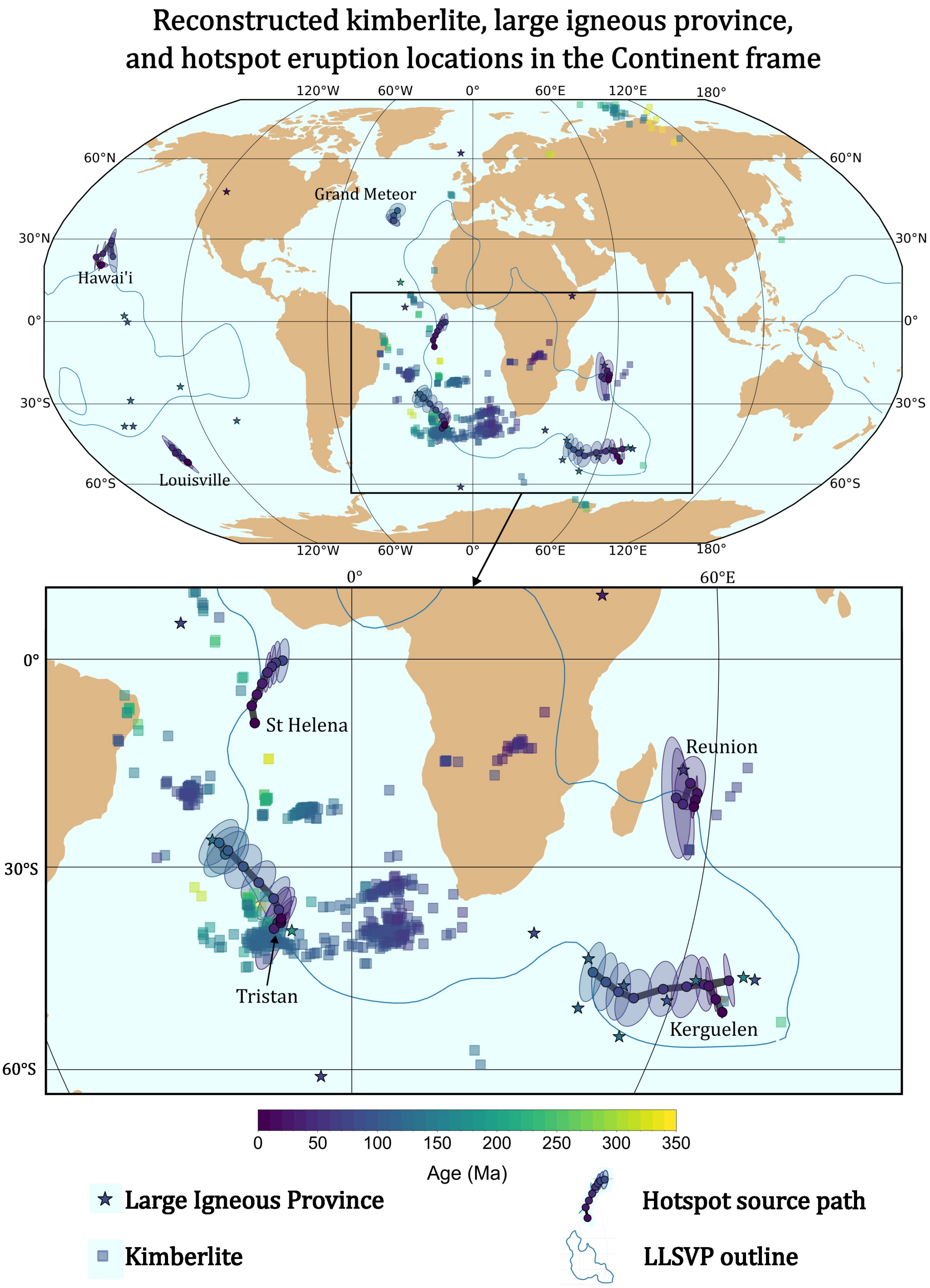

Figure 6. The reconstructed locations of kimberlite eruption sites (square), LIP eruption sites (star), and selected hotspot eruption sites in the continent frame. The LLSVP outline plotted is the 1% slow contour of the SMEAN tomographic model at 2800 km (Torsvik et al., 2014). LIP eruption sites and hotspot eruption sites are plotted with an uncertainty ellipse representing the age uncertainty in the base frame.

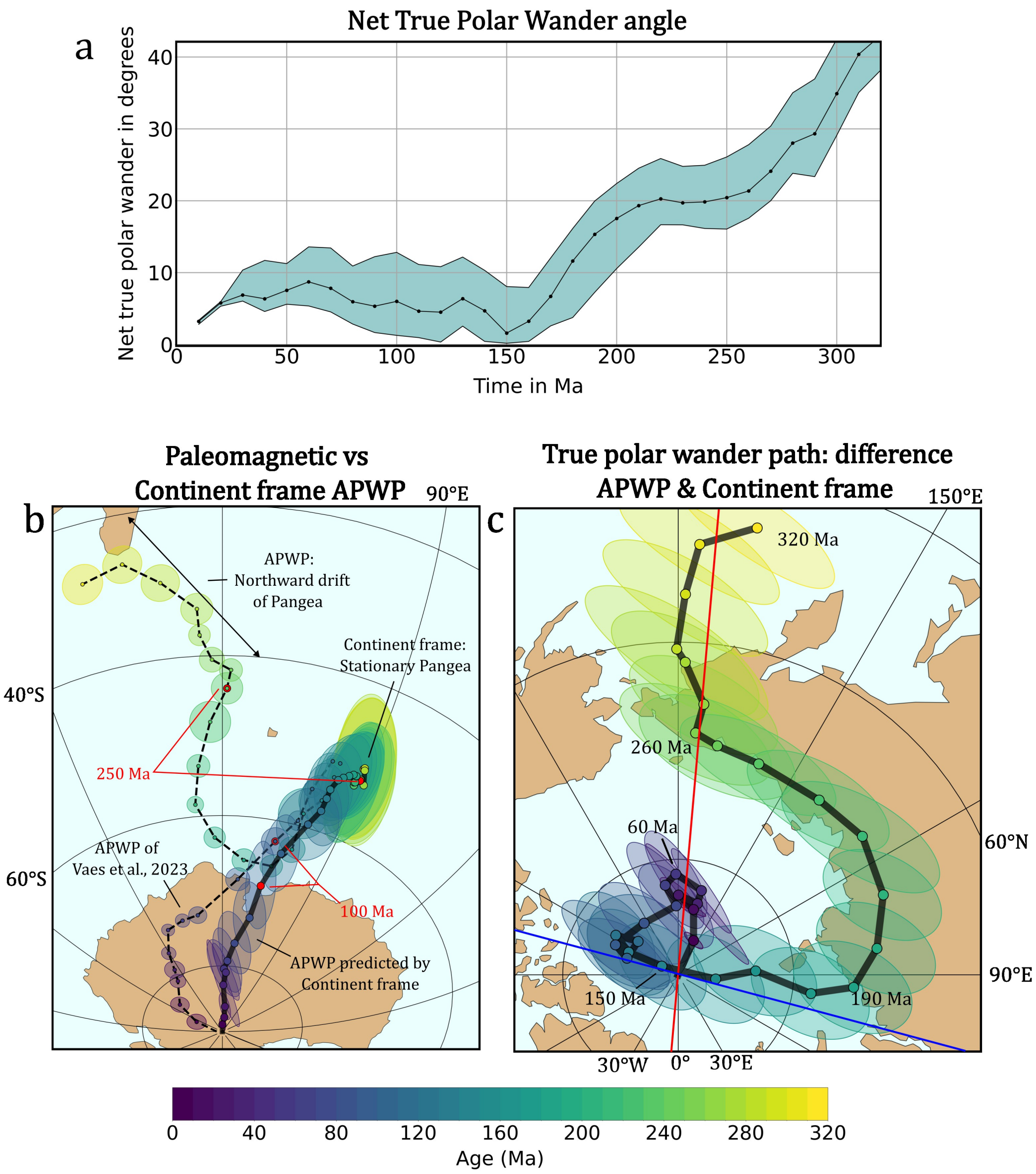

Figure 7. TPW predictions for the base frame. (a) Angular difference between the base frame and the paleomagnetic frame. (b) Paleomagnetic APWP (Vaes et al., 2023) (black dashed line) and synthetic APWP of the continent frame (black solid line) plotted on the South Pole. (c) True Polar Wander Path (TPWP) of the continent frame plotted on the North Pole. The axis around $0^o/15^o$W is marked with a blue line and the axis around $0^o/85^o$E is marked with a red line.

LLSVP from 320-120 Ma and shifted eastward until ~50 Ma, after which kimberlite volcanism stopped (Figure 6).

3.2.5 True polar wander

Finally, we computed a TPW frame for the last 320 Ma by placing the recent paleomagnetic reference frame of Vaes et al. (2023) in our base frame. Our continent frame predicts a net TPW rotation of ~9^o since 60 Ma (Figure 7a), consistent with estimates based on hotspot reference frames (Doubrovine et al., 2012; Vaes & van Hinsbergen, 2024). The TPW path suggests that cumulative TPW since 150 Ma is close to zero, as indicated by the spin axis plotting close to the geographic pole (Figure 7c). Between 150 and 190 Ma, a large shift in the estimated position of the spin axis predicts a TPW rotation of ~20^o about an equatorial axis located close to 0^{o}E.This is notably similar to previous estimates of TPW who indicated a ~20^o rotation during the Jurassic about an axis located at 0^o/11^{o}E (Torsvik et al., 2014) and 0^o/15^{o}W (Vaes & van Hinsbergen, 2024)

Prior to ~200 Ma, our continent frame minimizes the motion of Africa (i.e., Pangea) relative to the mantle (Figure 7b). As a result, the TPW path becomes very similar to the global APWP. The large swing observed in the global APWP during the Triassic, as well as the ~20^o shift in the pole position between 250 and 320 Ma due to the northward motion of Pangea, are also clearly visible in the TPW path. Consequently, the net angle of TPW predicted by the base frame increases back into geological time and becomes as much as 40^o at 320 Ma (Figure 7a). This is in sharp contrast with previous estimates of TPW by Torsvik et al. (2012, 2014), who reconstructed no significant TPW between 250 and 320 Ma. The difference between the TPW prediction of our base frame and the estimates of e.g., Torsvik et al. (2012, 2014) stems from the assumption that TPW occurred around an axis located at 0^o/11^{o}E. Instead, they interpreted the paleolatitudinal component of the motion of Pangea, which would correspond to an axis orthogonal to 0^o/11^{o}E (Figure 7c), as reflecting plate motion over the mantle. This implies that Pangea underwent major northward plate motion between 320 and 250 Ma. On the other hand, our base frame suggests that Pangea's northward drift was almost entirely a result of TPW. Although attributing all northward motion to TPW may be extreme, large amplitude TPW during this interval, as previously proposed by Le Pichon et al. (2023); Vaes and van Hinsbergen (2024) would have intriguing implications. Namely, it would predict that the LLSVPs, whose modern center of mass lies close to the inferred TPW axis at 0^o/11^{o}E of Torsvik et al. (2014), moved relative to the equator during a major phase of TPW (if they remained stationary in the mantle). We will return to the implications of such predictions in the discussion.

4 Discussion

4.1 A Solid Earth Integrated Reference Frame with a Continent Frame as basis

To use plate tectonic history to constrain the dynamic workings of the mantle requires placing plate tectonic reconstructions in a mantle reference frame. A 'reference frame' shows the motions of plates relative to a chosen fixed point, which introduces a problem: the mantle must accommodate the sinking of slabs, the upwelling of mantle below ridges, and the rise of mantle plumes and thus cannot be a fixed body of rock. In fact, plate motions in a mantle 'reference frame' are used to estimate how the mantle is moving. This is likely one of the reasons why different estimates of absolute plate motion, using hotspots, net lithosphere rotation, or true polar wander-corrected paleomagnetic frames combined with trench-slab correlations, or kimberlite/LIP-LLSVP correlations, do not yield identical results. All estimates of plate-mantle interaction are connected to each other via the relative plate model and give some assumed 'base' mantle reference frame, the motions of independent plate-mantle interactions, and rotation of the solid Earth relative to the spin axis (true polar wander) is constrained. We dub this a Solid Earth Integrated Reference Frame (SEIRF) (Figure 8), in which independent observations of plate-mantle interaction are tied together, sharing one key unknown: true absolute plate motion.

Our base frame of minimum continental plate velocity is based on the common null hypothesis in which horizontal motions in the mantle are insignificant. This is the same null hypothesis that implicitly underlies classical fixed hotspot frames (e.g. Müller et al. (1993)), namely that horizontal motions in the ambient mantle are negligible. This 'continent frame', previously used in combination with other approaches in the computation of a TRM (Müller et al., 2022), but not computed as a separate mantle reference frame, may thus approximate, but cannot represent true absolute plate motion. Moreover, it is important to note that this continent frame, like all other reference frames, is unique to a given relative plate motion model. Our version (Table 1) is thus specifically computed for the relative plate motion model of Merdith et al. (2021), and would require recalculation for plate models with different underlying Euler rotations or continent configurations.

The main advantage of the continent frame lies in the simple underlying null hypothesis. It can be calculated for all times a relative plate model, versions of which have been proposed for times as far back as 1.8 Ga (Cao et al., 2024). However, our estimates of uncertainty, which only illustrate the effect a ±5 Ma age uncertainty in the data that underlie the relative plate reconstruction, reveal the challenges constraining absolute plate motion in deep geological time (Figure 2e). For times between 350 Ma and 0 Ma, the relative positions of most continents are well-constrained through ocean basin reconstructions, and connections of continents within Pangea, and uncertainty in the relative plate model concerns mostly the reconstruction of oceanic plates, for which the continent frame is immune. For times prior to 350 Ma, and especially back into the Precambrian, a ±5 Ma age uncertainty is likely not conservative enough. Moreover, in absence of ocean basins to reconstruct, major uncertainty in pre-Pangean plate motions arise (Buffan et al., 2023; Seton et al., 2023), particularly in paleolongitude (e.g. Domeier and Torsvik (2019)), whose effects should be added to the age uncertainty. With error bars already exceeding absolute plate motions in the 10 Ma intervals we used, using just a ±5 Ma uncertainty (Figure 2e), absolute motions in continent or trench frames, or combinations thereof in a TRM (Müller et al., 2022) for times prior to 350 Ma must be considered unresolved.

On the other hand, our estimated uncertainty of the continent frame after 350 Ma may be a reasonable approximation, and the 10 Ma steps used in absolute plate motion exceed those uncertainties. The continent frame predicts an encouragingly good fit with the Pacific hotspot trails, and provides reasonable numbers for net rotation, TPW, trench kinematics, and hotspot drift rates, as well as LLSVP-kimberlite/LIP fits. We therefore consider it a good starting point to interrogate geodynamics and absolute plate motions.

4.2 Using coupled properties to investigate geodynamic signal and noise

One application of the SEIRF is that it allows interrogating the geodynamic plausibility of surprising spikes in the prediction of one of its kinematic components. Such spikes may indicate an interesting geodynamic conundrum that would present an opportunity to challenge the state-of-the-art but should first invite scrutiny of the relative plate model (see also Clennett et al. (2023)). From many candidates, we selected three examples to illustrate the use of independent properties coupled in the SEIRF. For instance, the continent frame predicts very high trench migration rate for several narrow subduction zones in the Tethys Ocean during the Triassic. If true, then this may inform about e.g. anomalously low viscosity in the mantle below the Tethys Ocean. However, given the challenges to accurately reconstruct intra-oceanic subduction history in ocean basins that have been lost to subduction (e.g. Vaes et al. (2019); Boschman et al. (2021)), this case is for now better conservatively interpreted as reconstruction error, and investigation into the relative plate model is the better first step.

Another interesting signal arises from the spike in net lithosphere rotation in the late Cretaceous caused by rapid motion of the Izanagi plate in the northwest paleo-Pacific realm (Lin et al., 2022). This spike in net rotation (Figure 5), could for instance suggest a weakened plate coupling to the asthenosphere facilitating rapid plate motion. An in-

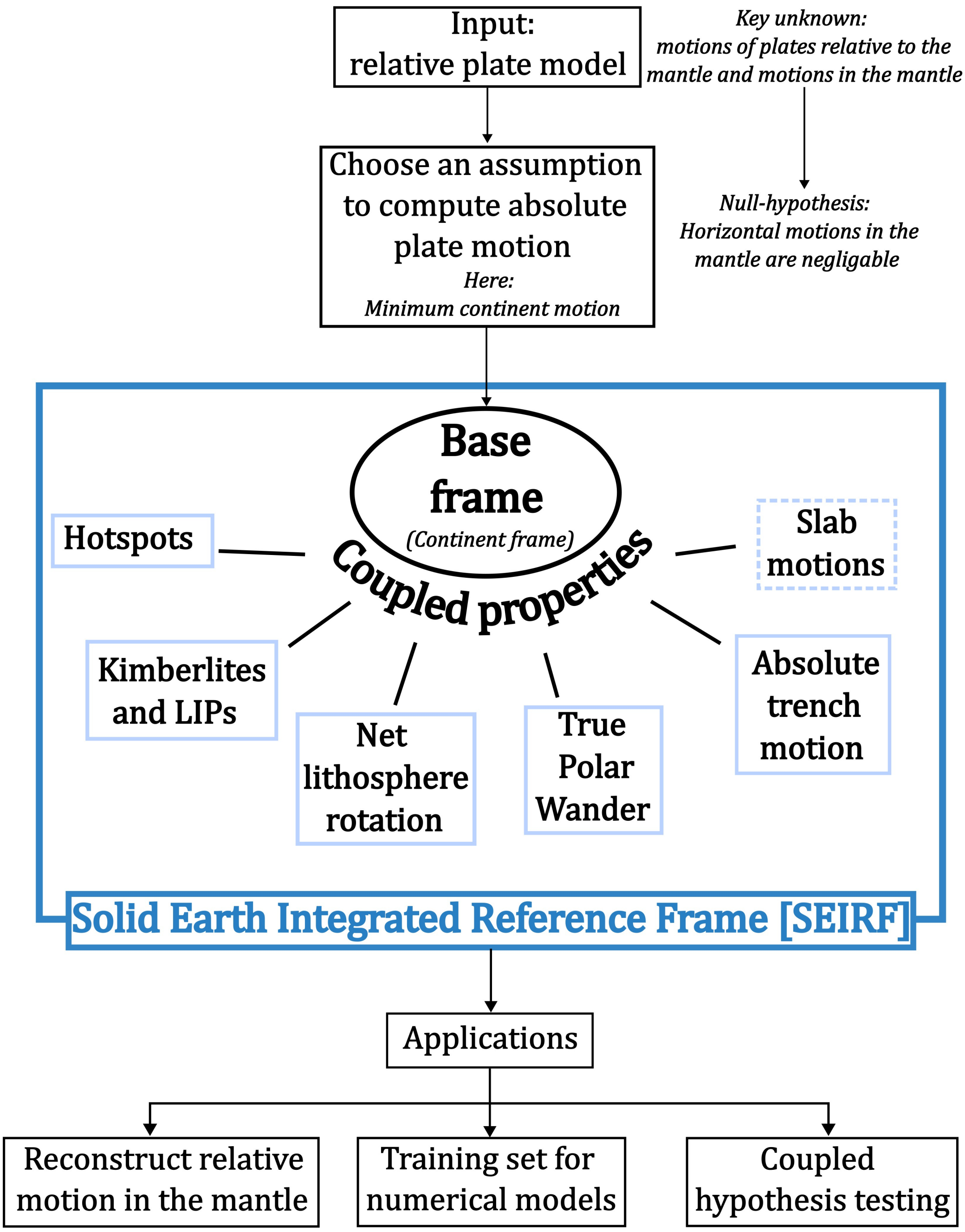

Figure 8. Schematic overview of the construction of the SEIRF and its components.

dependent evaluation of that implication could come from reconstructions of trench migration in the northwest paleo-Pacific realm. Orogenic belts on Kamchatka show evidence for long-lived intra-oceanic subduction in late Cretaceous to Paleogene time (Konstantinovskaia, 2001). The plate model of Merdith et al. (2021) did not include this detailed reconstruction of intra-oceanic subduction. However, those that do (Domeier et al., 2017; Vaes et al., 2019), constrained among others by independent paleomagnetic data, reveal rapid paleolatitudinal motion of intra-oceanic arcs, and associated trenches must have had high, long-lived trench retreat. Such rapid trench motions could form an independent argument for an anomalously weak mantle. Within context of the SEIRF, the regional plate reconstruction of e.g. Vaes et al. (2019) should be included into the global plate reconstruction, and the base frame and associated net rotation should be recalculated.

Finally, the phase of northward migration of Pangea in the late Permian to early Triassic that is observed in the paleomagnetic reference frame is absent from the continent frame. We computed this using the recent site-level based global apparent polar wander path of Vaes et al. (2023), but previous renditions based on traditional statistical procedures (Torsvik et al., 2012) showed the same pattern and would not significantly change this Pangean paleolatitudinal motion estimate. We find that within the continent frame, this migration is almost entirely attributed to TPW, with a magnitude as high as 40 ^{o} or more (Figure 7a). Major TPW moving Pangea northward was postulated before (e.g. Le Pichon et al. (2021)), but the magnitude far exceeds previous estimates based on finding common rotations around the current center of mass of the LLSVPs (Torsvik et al., 2014). We may use the different observations in the SEIRF to search where possible solutions may lie. The continent frame does not identify Pangean latitudinal motion as plate tectonic behavior, because moving the supercontinent at such speeds would lead to major friction. It would require long-lived extensive trench-parallel slab dragging of the subduction zones on the N-S trending Pangean margins, which also induces friction and has no local geodynamic driver (Spakman et al., 2018). The plate reconstruction of Merdith et al. (2021) does not contain major subducting oceanic plates attached to the supercontinent that could readily explain such movement. The sources of kimberlites in Southern Africa in this time window are predicted by the continent frame to remain stable and aligned with the LLSVPs, fitting previously inferred patterns (Torsvik, Burke, et al., 2010) whereas reconstructing northward Pangean plate motion would require comparable migration of kimberlite sources. Moreover, as we already pointed out in section 3.2.5, the previous estimates of Pangean TPW essentially assumed an axis of TPW within the heart of Pangea (Torsvik et al., 2014). If that axis would instead have been located far west or east, as appears to be the case for much of the Cenozoic (Doubrovine et al., 2012; Vaes & van Hinsbergen, 2024), paleolatitudinal motion of Pangea due to TPW could have been underestimated. Those combined observations could invite re-investigation of a hitherto controversial interpretation of Pangean paleolatitudinal change.

However, the continent frame, and the argument of slab dragging resisted by the mantle, relies on the assumption of negligible horizontal ambient mantle flow. Should a northward mantle flow have existed below Pangea, our base frame, and the interpretation of trench kinematics, would change. The geodynamic likelihood of such an alternative could be tested in numerical experiments. Moreover, such high TPW must reflect major changes in the Earth's moment of inertia, whose causes are typically best sought in the disturbing role in the subduction of slabs and the stabilizing role of LLSVPs (Steinberger & Torsvik, 2010). Interpreting a major syn-Pangea TPW phase thus invites investigating such causes of the change in Earth's moment of inertia, introducing more independent datasets. These examples illustrate that the SEIRF provides a framework to analyze one hypothesis using independent, but coupled constraints.

4.3 Reconstructing relative motions in the mantle

Because the continent frame holds no assumptions on mantle structure, the SEIRF provides a means to determine relative motions in the mantle, even if the base mantle reference frame is incorrect. In part, relative motions between geological observations that are tied to the mantle are already evident in the relative plate model. The best example is the evidence for hotspot drift, which follows from relative motion between the Pacific and Indo-Atlantic hotspots (e.g. Steinberger (2000)). In the same manner, relative motions between hotspots and kimberlite eruption sites could be constrained. But when placed in a base mantle reference frame, also motions relative to presumed plume sources (e.g., the edges of LLSVPs (Burke & Torsvik, 2004)) may be investigated. For instance, the continent frame suggests that the Pacific hotspots of Hawai'i and Louisville are almost stationary and that most plume motions occur in the Indo-Atlantic domain. Interestingly, the continent frame predicts motion of the Tristan, St Helena, and Kerguelen hotspot source (plume) along the LLSVP edge (Figure 6), which could be used to investigate a deep-mantle flow effect. Meanwhile, the kimberlite sources migrated in the direction of absolute plate motion, and more or less parallel to the southeastern margin of Africa, and could show the effect of the continental keel on a mantle plume. Such hypotheses naturally depend on the absolute plate model and change therein may change the hypotheses, but the relative motion between the Tristan hotspot source and the kimberlite source remains independent of the absolute plate model (similar to Rose et al. (2022)).

Further information on the causes of plume motion may come from incorporation of slabs imaged in the mantle (manifested as high seismic wave velocity anomalies) and subduction-related orogens into the SEIRF. Such correlations have been made before, and were used to determine slab sinking rates (van der Meer et al., 2010, 2018; Butterworth et al., 2014), as a semi-quantitative estimate of absolute plate motion (van der Meer et al., 2010), and even to interpret intra-oceanic subduction zone reconstructions (Van der Meer et al., 2012; Sigloch & Mihalynuk, 2013). By considering these slab-trench correlations within the SEIRF, we may reconstruct whether slabs, during or after their detachment, must have also moved horizontally relative to one another, and relative to plumes. The absolute direction of the reconstructed motion remains dependent on the absolute plate motion (opening possibilities to cross-correlate with e.g. seismic anisotropy (Wolf & Long, 2023)), but the relative motion does not. However, currently the localization of slab edges and midpoints remains qualitative and lacks detail (van der Meer et al., 2018). We identify quantifying the location of slab edges in the mantle in an objective manner as a key next step in correlating slabs to coordinates in the plate circuit.

4.4 SEIRF as training set to calibrate numerical models

Finally, the coupled observables of plate-mantle interaction in the SEIRF hold the potential for calibrating numerical mantle models. True 'absolute' plate motion is only known in controlled numerical experiments that include both plate motion and mantle flow, in which mantle flow influences the constraints on plate-mantle motion. Such an integrated numerical-kinematic approach was underlying the development of 'moving hotspot reference frames' (O'Neill et al., 2005; Torsvik et al., 2008; Doubrovine et al., 2012) in which numerical models were driven by an 'absolute' plate motion model first assuming hotspot fixity, after which absolute hotspot motion is predicted from model outcome (Doubrovine et al., 2012), an iterative process where the absolute plate motion is progressively modified to consider mantle motions predicted by the model. The SEIRF couples more, and independent constraints on absolute plate motion and mantle flow, and thus provides many novel and independent ways to train numerical simulations of solid Earth behavior (see also Ghelichkhan et al. (2024)). It is important to realize, however, that such iteratively trained models, such with moving hotspots, are not independent 'reference frames' as basis for geodynamic interpretations, but rather geodynamic interpretations themselves.

5 Conclusion

In this study, we introduce the Solid Earth Integrated Reference Frame (SEIRF) that couples kinematic observations of plate-mantle interaction and solid Earth change. With a relative plate model as basis, we started by constructing a mantle reference frame by minimizing continent velocity, under the simple null hypothesis that horizontal ambient mantle motions are negligible. We then used this 'base' frame to predict independent parameters resulting from plate-mantle interaction. In the current version of the

SEIRF, these include geological expressions of mantle plumes (hotspots, kimberlites, and large igneous provinces) relative to the edges of large low shear velocity provinces in the deep mantle from where they might derive, absolute trench motions, net lithosphere rotation, and true polar wander (by comparing to a paleomagnetic reference frame). Future additions may include e.g. the positions of subducted slabs imaged in seismic tomography relative to the associated subduction zones in the plate model. We illustrate the following applications of the SEIRF:

1. The investigation of anomalous behavior of kinematic parameters using coupled, independent observations. Anomalous behavior of one parameter may be corroborated by others or exist in isolation, which may aid identifying which observations challenge the state-of-the-art, and which may result from artifacts.
2. Constraining relative motions in the mantle. We show here how we may compute relative motion between different surface expressions of plume-plate interactions and deep-mantle structure. To further develop the SEIRF as a tool to better understand geodynamic processes, we consider quantifying slab locations in the mantle as a key next step. The additions of slabs into this frame in the future would open the possibility of understanding relative motions between slabs and between slabs and plumes. The SEIRF thus essentially flips the classical view of mantle reference frames: it places observations of mantle motion into a plate tectonic reference frame.
3. Training numerical models of solid Earth dynamics. Similarly to previous attempts to reconcile hotspot records with dynamic models of mantle flow, the constraints integrated into the SEIRF may be used to iteratively train 3D numerical simulations of mantle convection. The SEIRF thereby integrates different approaches to constraining absolute plate motion into one coupled system of kinematic constraints with one common unknown: true absolute plate motion.

Open Research Section

An updated version of the code published in Tetley et al. (2019) that we developed for the purposes of our paper, as well as the Python code needed to compute the data underlying the figures and to produce the figures is available on:

https://github.com/StefaniaWagenaar/SEIRF.git.

Acknowledgments

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