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Absolute plate motions since 130 Ma constrained by subduction zone kinematics

Simon Williams *, Nicolas Flament, R. Dietmar Müller, Nathaniel Butterworth

EarthByte Research Group, School of Geosciences, The University of Sydney, NSW 2006, Australia

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ABSTRACT

The absolute motions of the lithospheric plates relative to the Earth's deep interior are commonly constrained using observations from paleomagnetism and age-progressive seamount trails. In contrast, an absolute plate motion (APM) model linking surface plate motions to subducted slab remnants mapped from seismic tomography has recently been proposed. Absolute plate motion models (or "reference frames") derived using different methodologies, different subsets of hotspots, or differing assumptions of hotspot motion, have contrasting implications for parameters that describe the long term state of the plate–mantle system, such as the balance between advance and retreat of subduction zones, plate velocities, and net lithospheric rotation. Previous studies of contemporary plate motions have used subduction zone kinematics as a constraint on the most likely APM model. Here we use a relative plate motion model to compute these values for the last 130 Myr for a range of alternative reference frames, and quantitatively compare the results. We find that hotspot and tomographic slab-remnant reference frames yield similar results for the last 70 Myr. For the 130–70 Ma period, where hotspot reference frames are less well constrained, these models yield a much more dispersed distribution of slab advance and retreat velocities. By contrast, plate motions calculated using the slab-remnant reference frame, or using a reference frame designed to minimise net rotation, yield more consistent subduction zone kinematics for times older than 70 Ma. Introducing the global optimisation of trench migration characteristics as a key criterion in the construction of APM models forms the foundation of a new method of constraining APMs (and in particular paleolongitude) in deep geological time.

1. Introduction

Tectonic plates, and the network of plate boundaries that separate them, are in perpetual motion at Earth's surface. A remaining challenge is to derive models that fully integrate these surface plate motions with the dynamics of the underlying mantle (Torsvik et al., 2008). Observations from linear seamount chains (Morgan, 1972), paleomagnetic data (Irving, 1977) and more recently seismic tomographic imaging of subducted slab material (van der Meer et al., 2010; Butterworth et al., 2014) all provide evidence for the absolute motion of plates with respect to the deep mantle. Reconstructions of the Earth's plate tectonic system since the Mesozoic (Gurnis et al., 2012; Seton et al., 2012) have been built by combining geological and geophysical observations that constrain both relative plate motions (e.g. through magnetic anomalies, satellite altimetry data) and APMs. These reconstructions provide insights into the characteristics of Earth's plate tectonic system, such as its driving forces and the net rotation of the lithosphere (Ricard et al., 1991; Lithgow-Bertelloni et al., 1993; Torsvik et al., 2010), the rates of production of ocean floor (Seton et al., 2009), the organisation of the plates (Morra et al., 2013), and long-term sea-level fluctuations (Müller et al., 2008).

It is clearly desirable to know how the plates are moving relative to the deep Earth, yet, even for contemporary plate motion models (e.g. DeMets et al., 1994; Gripp and Gordon, 2002) spanning the Pliocene-present, significant discrepancies exist between alternative estimates of absolute global plate motions. Much of the uncertainty stems from the differences between APM models, a situation that provides a major challenge to assessing the relationship between surface plate motions and Earth's deep interior. Studies combining numerical and laboratory experiments and observations to constrain present day kinematics (e.g. Conrad and Behn, 2010; Funiciello et al., 2008; Lallemand et al., 2008; Husson, 2012) provide insights into what might be considered a geodynamically reasonable prediction of present-day plate behaviour. For example, Conrad and Behn (2010) used modelling and analysis of shear wave splitting to argue that net lithospheric rota-

* Corresponding author. Tel.: +61 2 935 12467.
E-mail address: simon.williams@sydney.edu.au (S. Williams).

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tion (NLR) is unlikely to ever exceed 0.26 deg/Myr. However, some contemporary reference frames based on different assumptions of hotspot dynamics yield much larger estimates for NLR, for example 0.44 deg/Myr (Gripp and Gordon, 2002; subsequently revised down to 0.34 deg/Myr, Zheng et al., 2010), and approaching 1.5 deg/Myr (Cuffaro and Doglioni, 2007).

In addition to NLR considerations, Schellart et al. (2008) proposed several further criteria to rank alternative global models of present-day APMs; they suggested that trench retreat should dominate over advance and that the absolute trench-perpendicular migration velocity should be minimised in the centre of wide subduction zones. A more general approach to plate boundary stability was proposed by Kaula (1975), who derived a series of models for contemporary APMs that minimised the translational motion of plate boundaries.

Using plate tectonic reconstructions with continuously closing plates (Gurnis et al., 2012), the characteristics of trench migration and NLR can be calculated over geological timescales for different reference frames. The results constitute an independent test of reference frames derived from hotspot trails or paleomagnetic data, allowing us to evaluate which published models give the most geodynamically plausible characteristics. Here, we compute absolute trench migration rates for eight APM models for the last 130 Myr. To complement our analysis we also compute global plate velocities and NLR, and explore the fit to observations of predicted hotspot trails. We investigate the long-term balance between trench advance and retreat, test how these results are dependent on the APM model, and explore the idea that trench migration rates can be used to rank alternative reference frames.

2. Formulation of analysis

2.1. Relative plate motions

We use the relative plate motion (RPM) model of Seton et al. (2012) with updates for the Arctic based on Shephard et al. (2013). This model incorporates continuously closing plates (Gurnis et al., 2012) providing a continuous description of plate boundaries and velocities for the last 200 Myr. The RPM model is constructed using a plate hierarchy with Africa at the top, and all other plate motions are defined through relative motions between pairs of plates (with the exception of plates in the Pacific realm prior to 83 Ma). The APM models considered in this study are all defined in terms of the absolute motion of Africa, the continent typically chosen to link the plates to the deep Earth on the basis that it has been the most stable major plate since the breakup of Pangea as it has been surrounded by spreading ridges (e.g. Burke and Torsvik, 2004). The absolute motion of other plates depends on a combination of the Africa APM and the relative plate motions within a chain that links this plate to Africa – for example, the absolute motion of the Australian plate depends on an RPM chain through East Antarctica to Africa. In this sense, uncertainties in APMs increase for plates with long plate chains to Africa. Using the same RPM model, we test a range of APM models derived using three broad methodologies: hotspot trails, paleomagnetic data, and matching of past subduction zone locations to fast seismic tomography anomalies in the lower mantle.

2.2. Absolute plate motions

Absolute plate motions broadly describe how lithospheric plates move relative to the Earth's deep interior. Classic attempts to derive APM models stem from the theory that hotspot trails are generated by mantle plumes rising from the deep mantle, and that age-progressive trends of seamounts along linear volcanic trails reveal the motion of the plates relative to these hotspots, and therefore the Earth's deep interior. Hotspot reference frames are underpinned by radiometric dating of samples recovered from such trails within the Atlantic, Indian, and Pacific ocean basins. Two significant challenges are to combine information from trails on different plates (due to uncertainties in RPM), and to account for possible hotspot motions (e.g. Steinberger et al., 2004; Doubrovine et al., 2012).

Müller et al. (1993; herein denoted M1993) defined APMs relative to Africa using hotspot tracks within the Indian and Atlantic oceans, assuming relative fixity of hotspots within the Indo-Atlantic realm from 130 Ma to present-day. Combining information from Indo-Atlantic trails with models of mantle convection, O'Neill et al. (2005; herein denoted O2005) proposed a model of APMs relative to Africa that incorporated estimates of hotspot motions. While taking lateral motion of plumes in the mantle into account is an improvement compared to fixed hotspots, the APMs derived using mantle convection models are only valid within the physics and parameters of a given geodynamic model. There is therefore some inconsistency when APMs based on geodynamic models are used as boundary conditions of mantle flow models based on distinct physics, assumptions and parameters (see discussion in Rudolph and Zhong, 2014).

Global analyses of plate motions relative to hotspots are complicated by the difficulty in constructing a well-constrained RPM model that links the Pacific and Indo-Atlantic regions. A longstanding issue within global RPM models surrounds the Cenozoic motion within West Antarctica. An accurate quantification of this motion is difficult, but it is crucial to the identification of large-scale relative motions between hotspots in the Pacific and Indo-Atlantic domains (Cande et al., 2000; Sutherland, 2008). Due to these RPM uncertainties, the numerous age-progressive volcanic trails recorded on the Pacific plate and Pacific APMs have typically been studied separately from the Indian and Atlantic realms (e.g. Wessel and Kroenke, 2008). Even within the Pacific domain alone, the analysis is complicated by evidence for relative motion between hotspots, notably Hawaii and Louisville (Koppers et al., 2012).

Attempts to model APMs and hotspot motions have yielded two generations of global moving hotspot models where the trails of age-progressive volcanism within the Indian, Atlantic and Pacific ocean basins are reconciled (Steinberger et al., 2004; Torsvik et al., 2008, herein denoted T2008; Doubrovine et al., 2012, herein denoted D2012). These models focus on volcanic trails associated with 'deep' plumes, whose motions were predicted using geodynamic models of mantle flow using backward advection of the present-day temperature field derived from seismic tomography. Importantly, APMs derived using this approach are only strictly valid within the physics and parameters of the geodynamic model used. In particular, moving hotspot models without lateral viscosity variations do not allow differential rotation between the lithosphere and lower mantle. Global reference frames assuming either fixed or moving hotspots both yield reasonable fits to age samples for times younger than 50 Ma, but fixed hotspot models yield unacceptable misfits for the 50–80 Ma period compared to moving hotspot models (Doubrovine et al., 2012).

As an alternative to using hotspot trails, reference frames have also been derived based purely on paleomagnetic data (Schettino and Scotese, 2005; Torsvik et al., 2012). Two widely recognised limitation of APM models based on paleomagnetic data alone are that they lack longitudinal constraint, and that they may contain components of true polar wander (TPW; e.g. Steinberger and Torsvik, 2008). Nonetheless, for times prior to the oldest preserved seamount chains, paleomagnetic data are the most powerful constraint on absolute plate positions. A recently developed approach to constrain paleolongitude through deep time is the mapping of slab remnants within the mantle from seismic tomography

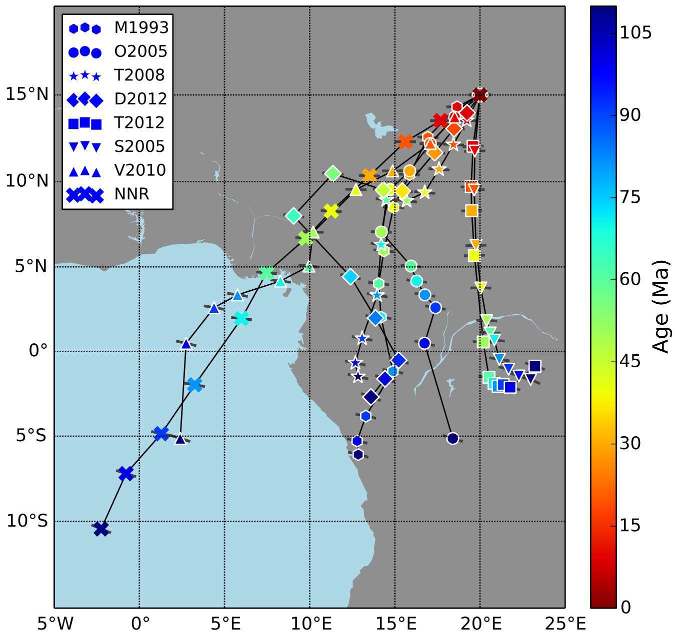

Fig. 1. Motion paths of a point in Africa for the last 130 Myr according to different absolute plate motion (APM) models, as listed in the legend. Tick marks along each curve show the rotation of Africa (relative to an E–W orientation at 0 Ma). Differences between APM models arise both from the absolute position of Africa, and the evolution of the rate and direction of motion.

(van der Meer et al., 2010). Combining these mapped slab remnants with an RPM model, and assuming slabs sink vertically at an average rate determined to be ∼12 mm/yr, van der Meer et al. (2010) defined an APM model with constraints on longitude for the last ∼250 Myr. For the last ∼130 Myr the slab-remnant approach implies westward longitudinal shift of all plates by up to 18° compared to APM models derived from hotspot trails.

We test the van der Meer et al. (2010; herein denoted V2010) reference frame as well as two purely paleomagnetic reference frames: those of Schettino and Scotese (2005; herein denoted S2005), and the ‘Running Mean’ reference frame of Torsvik et al. (2012; herein denoted T2012). We also consider a ‘no-net rotation’ APM model derived for the last 130 Ma by removing the net rotation stage pole at 1 Myr intervals, and determining the APM path for Africa that minimises NLR (see also Shephard et al., 2014). We confine our analysis to the last 130 Myr, since this is the limit of prediction of the reference frames constrained by hotspot trails. Fig. 1 shows how the absolute motion of a point within Africa varies between the different APM models (cf. Doubrovine et al., 2012). All models consistently show an overall northward motion of Africa since the Early Cretaceous, but with significant variations in the magnitude of eastward motion, and significant variations in the magnitude and direction of Africa motion over shorter (10–30 Ma) time frames.

2.3. Computed quantities

The primary focus of our study is to compute trench migration rates for alternative APM models. We first compute topologically closed plate boundaries in 1 Myr intervals, then for each time step, the subduction zones are extracted and resampled to regular spaced segments of 1 arc degree, and the trench-normal velocity is computed for each point using the local orientation of the subduction zone and the plate kinematics (APM + RPM; Fig. 2 and Fig. S1). For each subduction zone segment, the migration rate is defined as the component of the absolute velocity of the subduction trench orthogonal to the orientation of the line segment (e.g. Lallemand et al., 2005). We analyse trench migration through time for each APM model (Figs. 3 and 4).

We calculate NLR for each APM model (Fig. 5a) following the method outlined by Torsvik et al. (2010). For consistency with previous studies, we calculate NLR from absolute plate velocities averaged over 10 Myr on a mesh of points with a mean spacing of ∼50 km. We also compute the L_2-norm (i.e. the mean amplitude of the velocity field) of all surface plate velocities for each time interval (Fig. 5b), which is expected to be proportional to NLR (Alisic et al., 2012; Fig. 5c). For times older than 83 Ma, the Pacific plate is surrounded by subduction zones and cannot be linked to Africa within an RPM model (Seton et al., 2012). For all our calculations, absolute motion of the Pacific plate for the 130–83 Ma period are derived using stage rotations calculated from the Pacific absolute motion model of Wessel and Kroenke (2008).

We perform some simple calculations to assess the degree to which different APM models satisfy hot spot trails. For a uniform comparison across all models, we generated trail predictions for seamount trails in the Atlantic, Indian and Pacific oceans and the Tasman Sea, combining the Seton et al. (2012) RPM model and using a fixed hotspot approximation. Comparisons are both qualitative, plotting predicted trail paths against observed seamount chains (Fig. 6), and quantitative, using a simple distance metric to assess the misfit between observed and predicted ages for sites that have been sampled and radiometrically dated (see Supplementary section B). Where available, we compared predictions from moving hotspot models using individual hotspot motions and alternative plate chains linking the Pacific with Africa APM (see Supplementary section B for a more detailed description).

3. Results

3.1. Trench kinematics

We calculate trench kinematics through time for all tested APM models (Figs. 2 and S1). In particular, we focus on the trench-orthogonal absolute trench migration (Schellart et al., 2008). Trench advance and retreat are plotted with red and blue arrows respectively, with each of the plotted time steps showing a greater tendency for trench retreat. The most rapid trench migration velocities correspond to the retreating intra-oceanic subduction zones of the western Pacific, where, the RPM model is likely to be poorly constrained. In that region, relative kinematics of back-arc spreading rely on fragments of paleomagnetic evidence, and the absolute motions of trenches within Melanesia and the Izu-Bonin–Marianas system are computed using long plate chains to Africa. Nevertheless, magnitudes less than 100 mm/yr are well within the range of estimates for present-day kinematics in this region (Funiciello et al., 2008; Schellart et al., 2008).

Trench migration tends to be smaller in amplitude along the convergent margins of major continents (e.g. the western margins of North and South America and the southern margin of Eurasia). There is, however, significant variation in trench motion along the margins of these continents since 130 Ma, following a pattern that is highly dependent on the APM model used. Fig. 2 shows a small subset of the results for two different APM models at three different time periods to give a sense of how different APM models predict different patterns of trench kinematics. Three plate kinematic snapshots are shown for APM models D2012 and V2010. Notable differences between the temporal pattern of trench dynamics are observed at each stage. For example, APM model V2010 predicts moderate trench retreat along the western margin of North America at 75 and 65 Ma followed by more rapid trenchward migration of the overriding plate around 55 Ma. In contrast, APM model D2012 produces much more rapid trench retreat at 75 Ma, and an almost stationary trench at 55 Ma.

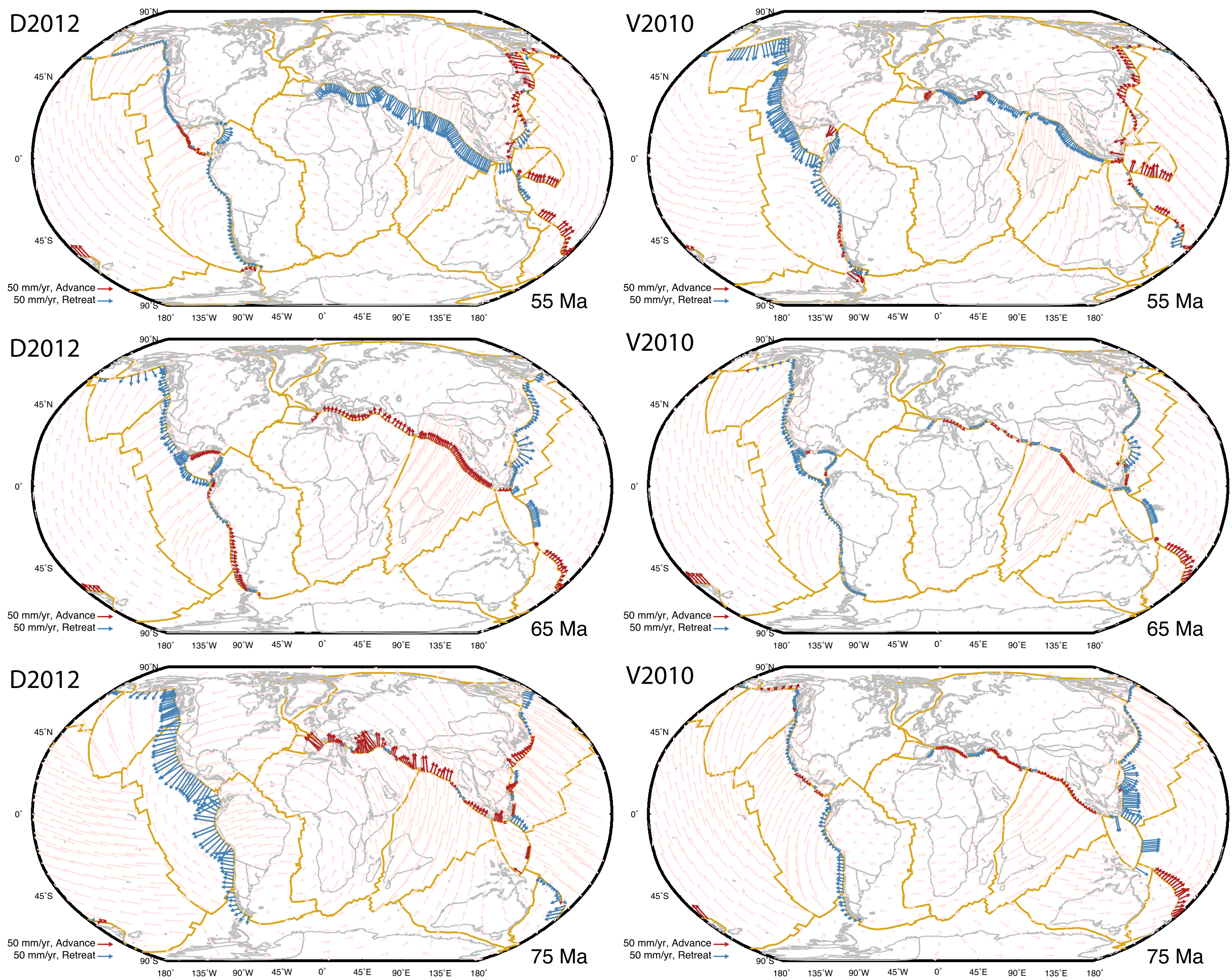

Fig. 2. Examples of contrasting patterns of trench advance and retreat for two of the APM models tested at three times during the Late Cretaceous and early Cenozoic. The left panels were calculated using the hotspot reference frame of Doubrovine et al. (2012) and the right panels were calculated using the APM model of van der Meer et al. (2010). Such differences in subduction zone kinematics are summarised in the histograms plotted in Fig. 3.

To compare the overall trench-normal trench migration rates, V_T, for different APM models, we represent the results as histograms of the global distribution of values at 1 Myr intervals (Fig. 3). Rates calculated with velocities averaged over 5 and 10 Myr give similar results (Fig. S3). Positive values represent trench retreat and negative values trench advance, and the colour intensity is proportional to the number of subduction zones moving at given velocities, subdivided into 5 mm/yr bins. Histograms for the most recent time intervals are comparable to those computed by Schellart et al. (2008).

Qualitatively, the characteristic trend for all models is for a distribution that straddles zero but is skewed slightly towards trench retreat (the plots are more blue than red). For the four hotspot reference frames (Figs. 3a–d), a first-order observation is that trench migration rates under 30 mm/yr dominate for much of the Cenozoic, but rates become progressively more scattered before 50 Ma. Second-order trends include a phase of highly dispersed trench migration rates in APM model O2005 from 50–60 Ma, and a large proportion of advancing trenches in APM model D2012 between 60–70 Ma (Figs. 3b and 3d).

Compared to hotspot APM models, models derived from paleomagnetic data (S2005 and T2012) show a more dispersed pattern of trench migration rates for the entire 0–130 Ma time period (Fig. 3). By contrast, reference frames based on slab remnants (V2010), or assuming no-net-rotation of the lithosphere result in distributions which, qualitatively, imply trench migration rates closer to zero, and with a distribution which does not appear significantly more scattered with increasing age (Fig. 3).

We compute some diagnostic measures for all the models to compare and contrast the geodynamic characteristics implied by the different APM models, following the approach of Schellart et al. (2008). Fig. 4 shows the standard deviation of trench migration (Fig. 4a), the percentage of retreating trench segments (Fig. 4b), the percentage of segments with trench migration >30 mm/yr (Fig. 4c) or < -30 mm/yr (Fig. 4d), and the mean absolute value of trench motion (Fig. 4e). Each quantity is calculated at 1 Myr intervals, then plotted as a 5 Myr moving average. Where possible, the value calculated by Schellart et al. (2008) for the highest-ranked model of contemporary plate motions, computed using APM model O2005 but an RPM for contemporary plate motions (DeMets et al., 1994), is plotted for comparison (denoted by triangles at 0 Ma in Fig. 4).

The standard deviation and mean norm of V_T both vary between 15 and 35 mm/yr for most APM models. In the latter case, the range is consistent with the value of ~21 mm/yr computed by

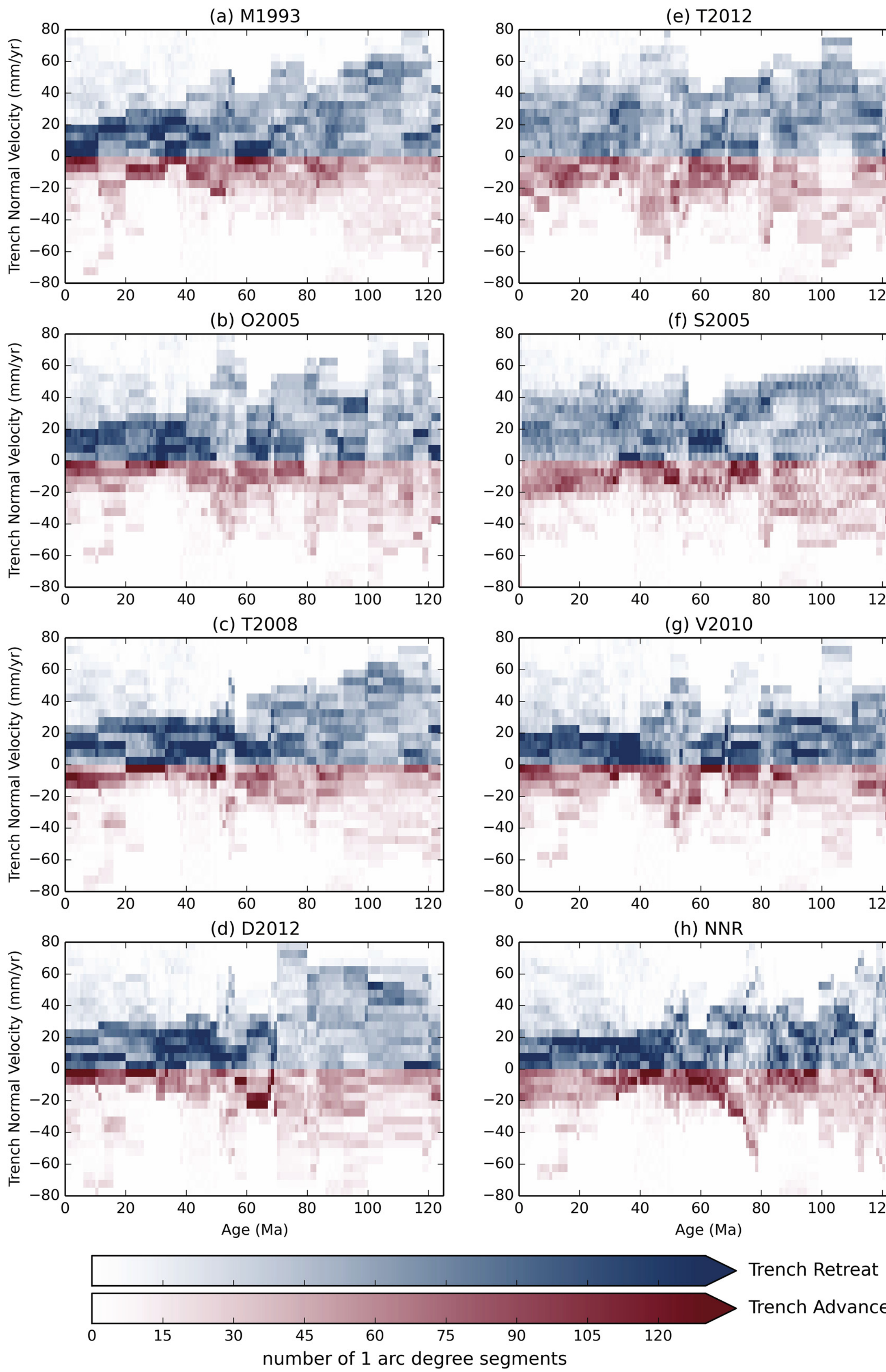

Fig. 3. Histograms of the trench-normal overriding plate velocities computed for eight alternative APM models using the same RPM model and plate boundaries. APM models based on hotspots are shown in the left column, paleomagnetic APM models in the upper right, and slab-remnant and NNR models in the lower right. Colours are proportional to the number of one-arc-degree segments in each velocity bin of 5 mm/yr. Models consistent with global subduction dynamics are dominated by trench retreat (blue) and minimise high-frequency fluctuations in mean trench velocities. (For interpretation of the colors in this figure, the reader is referred to the web version of this article.)

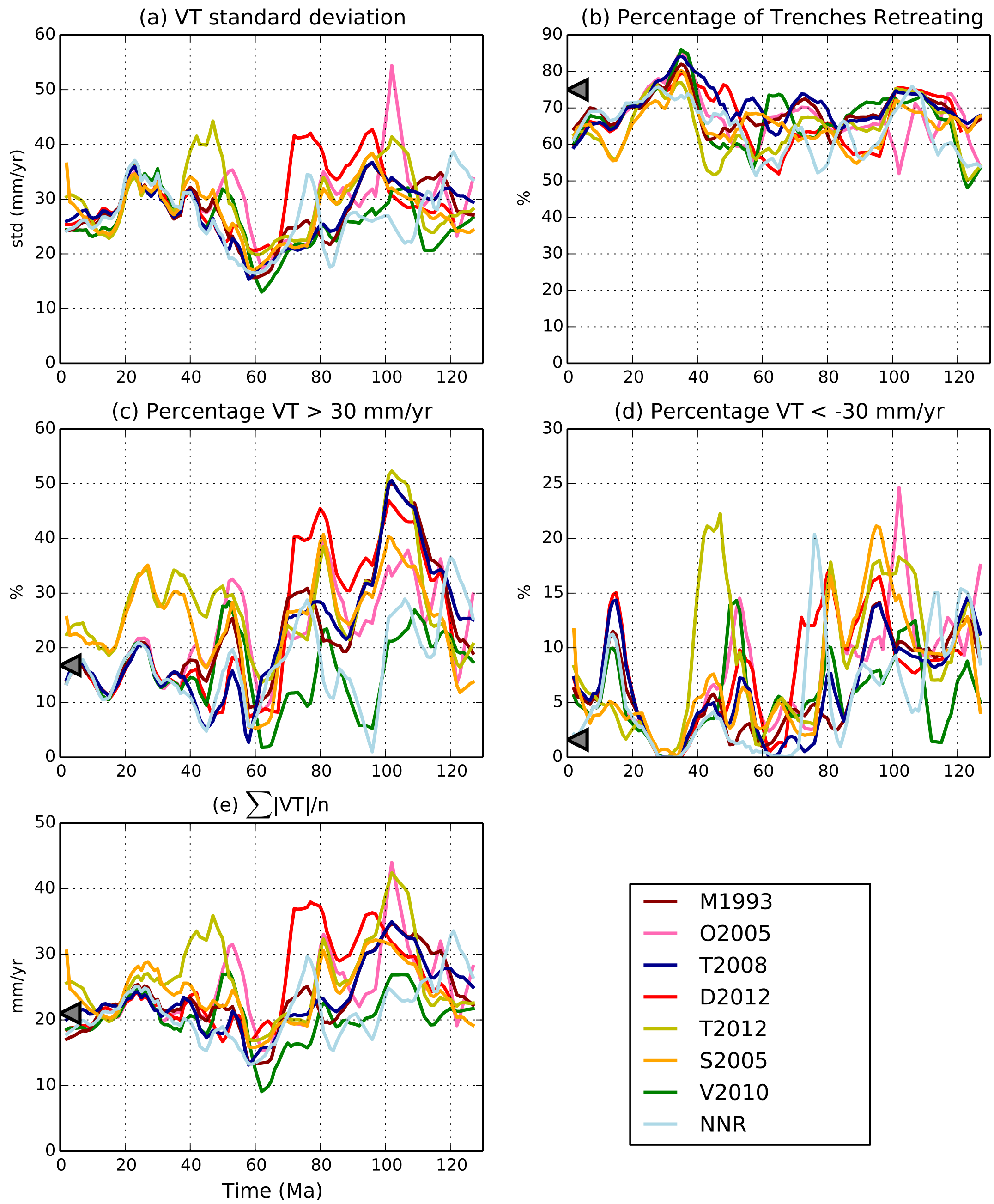

Fig. 4. Measures of overall trench migration behaviour through time computed at 1 Myr intervals for each of the reference frames listed in the legend, then plotted as 5 Myr moving averages. (a) Standard deviation of the global trench migration rates, for which low values are considered more reasonable; (b) Percentage of retreating trenches, for which higher values are preferred; (c) Percentage of trenches retreating at greater than 30 mm/yr, for which lower values are preferred; (d) Percentage of trenches advancing at greater than 30 mm/yr, for which lower values are preferred; (e) Mean absolute value of trench motion, for which lower values, indicating greater trench stability, are preferred. Grey triangles in (b) to (e) show the values for present-day kinematics for the preferred model of Schellart et al. (2008).

Schellart et al. (2008) for the present-day. The percentage of retreating trenches remains below 25% for non-paleomagnetic APM models back to 50 Ma, compared to the present-day estimate of ∼18% (Schellart et al., 2008). The present-day percentage of retreating segments is 60–65%, which is slightly less than the ∼75% calculated by Schellart et al. (2008). The percentages of segments advancing faster than 30 mm/yr (2–12%) are greater than the 1.6% in the highest-ranked model of Schellart et al. (2008). These differences are likely attributable to the differing RPM model since Schellart et al. (2008) used APM model O2005 included in the present analysis. Our values for periods earlier in the Cenozoic fall within a range consistent with Schellart et al.'s (2008) present-day values.

3.2. Net lithospheric rotation

Our results for NLR over the last 130 Myr (Fig. 5a) are an expansion of those of Torsvik et al. (2010), who compared a subset of hotspot models. The hotspot APM models we explored all show a long term decline in net rotation with age since the early Cretaceous (Fig. 5a), which Torsvik et al. (2010) attributed to increasing uncertainty in the kinematics and plate boundary configurations of their RPM model with age. The computed L_2-norm velocity also produces a long-term decline, even for the NNR model (Fig. 5b). The strong correlation between the magnitudes of NLR and L_2-norm velocity (Alisic et al., 2012) is illustrated by Fig. 5c, which for all APM models shows a linear relationship for ages

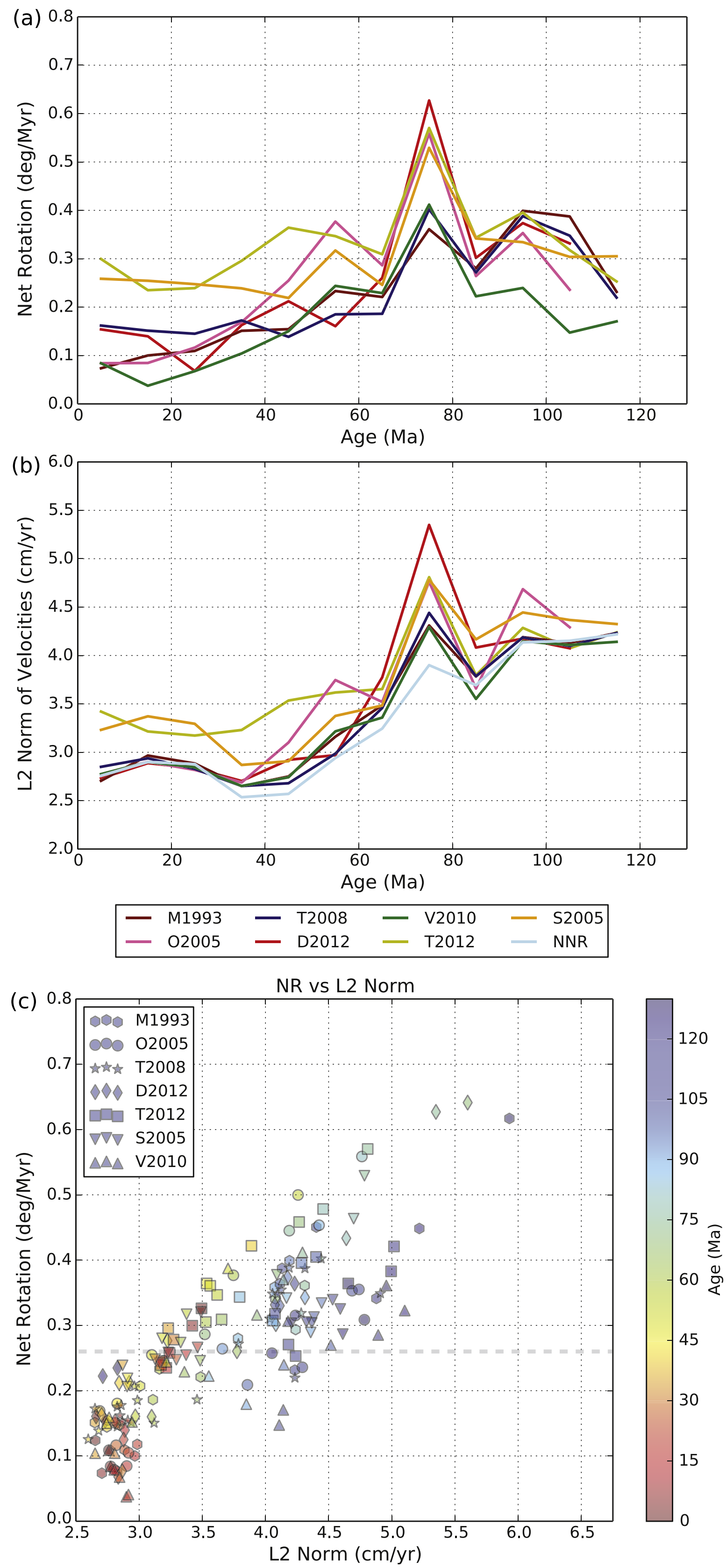

Fig. 5. (a) Net lithospheric rotation (NLR) for alternative APM models; (b) L_2-norm of the velocities for different APM models; (c) Crossplot of NLR and L_2-norm. For consistency with previous studies, values are calculated using velocities averaged over 10 Myr periods.

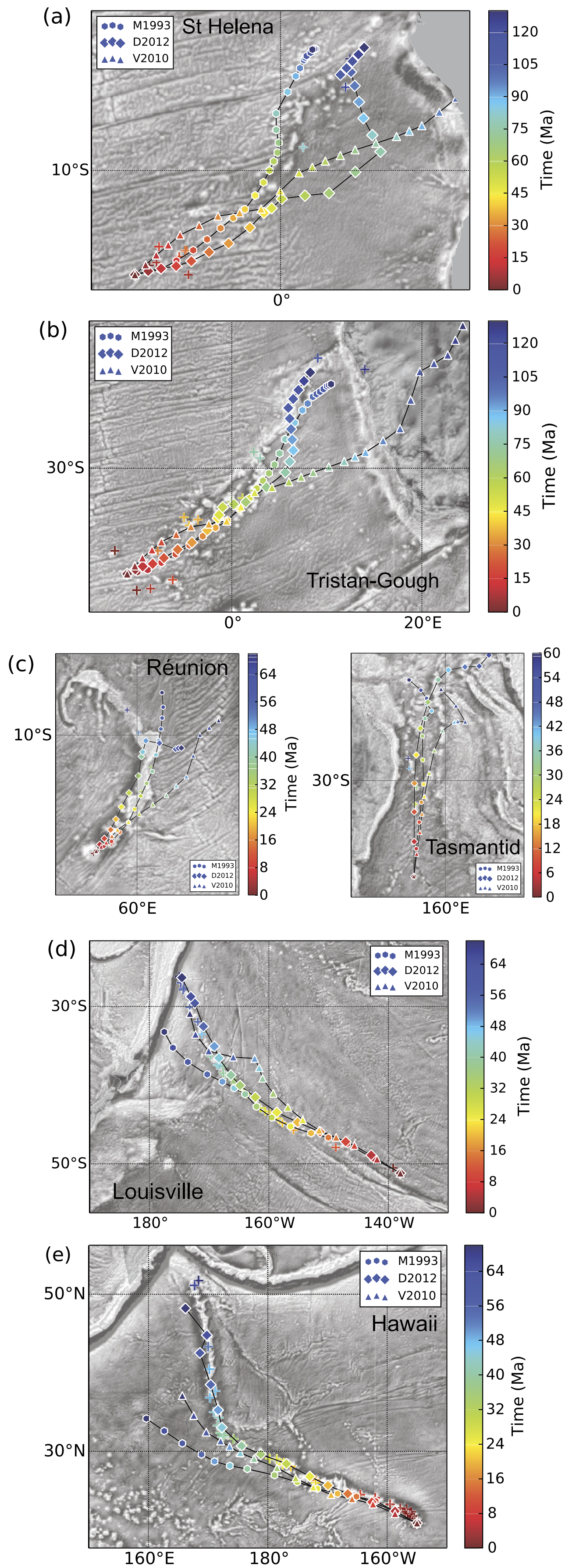

Fig. 6. Predicted hotspot trails calculated for selected APM models. (a) Tristan-Gough, (b) St Helena, (c) Réunion, (d) Tasmantid, (e) Louisville. Sample sites are illustrated as semi-transparent crosses with the same colour scale as predicted trails. We plot the M1993 fixed hotspot model and the V2010 slab remnant APM model combined with the Seton et al. (2012) RPM model and no individual hotspot motion; for the D2012 model, trails are computed using the RPM model and individual hotspot motions used in that study. See Supplementary section B for a more detailed description of data used. For trails not on the African plate, calculations depend on the plate chain and rotation parameters used to link these plates to Africa. Both our RPM model, and the RPM models underpinning previous global hotspot models (T2008, D2012), rely on relative motions between East and West Antarctica from ∼26 Ma to at least ∼45 Ma that are subject to large uncertainties (Cande et al., 2000). Using more tightly constrained kinematic parameters for E–W Antarctica (Granot et al., 2013) within an otherwise unchanged RPM model, predicted trails for the Emperor section of the trail associated with Hawaii shifted >400 km to the east at ∼40 Ma.

younger than ∼60 Ma, becoming more scattered for older times. Compared to hotspot APM models, model V2010 produces a similar though less pronounced declining trend in NLR since 130 Ma. The two paleomagnetic APM models tested yield NLR similar to other models at the oldest times (>0.25 deg/Myr), but rather than declining, large NLR persists to present-day.

Variations in NLR over short (∼10–20 Myr) timescales have been attributed either to changing area and velocity of the Pacific plate, or to the large changes in the velocity of the Indian plate (Torsvik et al., 2010). These latter events may be linked to the large spike in NLR apparent in APM models O2005 and V2010 between 50–60 Ma. Another explanation for why the 50–60 Ma peak in NLR is most apparent in APM model O2005 is the fitting of two hotspot tracks (Seychelles and Deccan Traps) for the Réunion plume during that period. A second period of large NLR and L_2-norm velocity is observed for all models from 70–80 Ma, most pronounced in the D2012 and coinciding with a phase of rapid northwestward motion of Africa in this model that is not seen in other models (Fig. 1). We note that some difference between our results and previous ones is expected due to the use of alternative RPM models, and in particular, computing all absolute velocities for the Pacific domain using a Pacific mantle hotspot (Torsvik et al., 2010).

3.3. Fit to observations along hotspot trails

The hotspot APM model giving the smallest RMS mismatch (Table 2) varies between different trails, largely reflecting the methods used to constrain them. Model M1993, itself based on a fixed hotspot assumption for the Indo-Atlantic hotspots, best reconciles observations for trails in the Atlantic. The lowest misfit for the Réunion and Tasmantid chains is given by model T2008, for which observations from the Réunion trail were one of the constraints. Model D2012 gives the lowest misfit for the Pacific trails – observations from both Louisville and Hawaii–Emperor trails were used in the derivation of this model. Between 0–100 Ma, model V2010 is derived by applying longitudinal shifts to model O2005, which result in a significantly larger RMS mismatch for the Tristan-Gough and Réunion trails, but a lower mismatch for Hawaii and St Helena (Table 2). Paleomagnetic models S2005 and T2012 give significantly higher RMS values, at least double the best-fitting model for each trail (Table 2).

Fig. 6 shows predicted trails for three APM models – a fixed hotspot model (M1993), a moving hotspot model (D2012) and the V2010 model which is decoupled from any hotspot model. In order to present the D2012 model in a self-consistent manner, these trails are derived using individual hotspot motions, and using an alternative global RPM model in which the Pacific is linked to the Atlantic through the Lord Howe Rise before ∼45 Ma (Doubrovine et al., 2012). A closer agreement between predictions and observations is expected for the D2012 model, and is particularly apparent for the Hawaii–Emperor. For trails that lie either entirely

Table 1
Values summarising the statistical measures shown in Fig. 4 for different time periods. The analysis is broken into two distinct time periods: A/ 70–0 Ma, during which hotspot-based APM models are relatively well constrained; and B/ 130–70 Ma, during which constraints from hotspots are much less robust. Bold numbers highlight the 'optimum' APM model for each criterion out of the seven previous models considered. Moving hotspot reference frame T2008 outperforms other reference frames for the 0–70 Ma period. An NNR reference frame would be preferred to published models in 3 of the five categories during the 0–70 Ma time period (denoted by underlined numbers). Over the period 70–130 Ma, during which constraints from hotspot trails are scarce, the slab remnant APM model V2010 performs better than other models. Note that results for APM model D2012 are only calculated back to 124 Ma.

	StDev (mm/yr)	% Retreating	% >30 (mm/yr)	% <−30 (mm/yr)	$\sum \lvert V_T \rvert /n$ (mm/yr)
A: 0–70 Ma					
M1993	26.1	69.1	16.7	**3.7**	20.5
O2005	27.3	69.1	17.8	4.9	21.5
T2008	**25.8**	**71.0**	**14.2**	4.1	20.2
D2012	27.4	67.6	14.4	5.0	21.1
T2012	29.1	63.4	25.4	6.4	24.6
S2005	29.3	65.5	21.9	4.2	23.3
V2010	26.2	68.1	14.6	4.4	**19.4**
NNR	*25.7*	*66.5*	*14.1*	*2.5*	*19.3*
B: 70–130 Ma					
M1993	30.0	69.0	32.0	8.8	27.3
O2005	32.0	64.9	28.6	11.6	27.5
T2008	29.7	**69.5**	32.8	8.7	27.1
D2012	67.0	62.4	34.9	12.4	63.3
T2012	31.1	66.1	30.9	12.1	28.5
S2005	29.8	66.0	32.3	10.8	27.5
V2010	**25.4**	66.2	**17.2**	**6.8**	**21.3**
NNR	*28.0*	*61.5*	*20.9*	*9.2*	*23.8*

or predominantly on the African plate, the V2010 model shows significant offset to the observations under a fixed hotspot approximation, implying rapid hotspot motion.

4. Discussion

4.1. Long-term trends in trench migration

Our analysis suggests that the long term, global average tendency of trenches is for retreat to dominate over advance (Figs. 4b, c, d), consistent with the kinematics of contemporary plate motions (Schellart et al., 2008). This result is particularly clear in the hotspot APM models for the well constrained 0–70 Ma period, and within the slab APM model for the entire 0–130 Ma period considered (Table 1). APM models based on paleomagnetic data alone yield a more dispersed distribution of trench migration than APM models based on hotspot trails or slab remnant mapping (Fig. 3). The contrast between more or less dispersed histograms mirrors the contemporary plate motion calculations of Schellart et al. (2008), who found that trench-normal motions have a relatively narrow distribution around zero for their preferred APM model (O'Neill et al., 2005), whereas the HS3 APM model of Gripp and Gordon (2002) predicts a broader range of trench-normal motions – including rapid retreat, and particularly rapid advance – argued to be geodynamically less plausible. Paleomagnetic APM models are only constrained in latitude, and our comparison demonstrates the degree to which the longitudinal constraint offered by hotspot trails or slab remnant mapping yields a more geodynamically reasonable set of reconstructions. Conversely, our results show that more generally, paleomagnetic APM models could be improved by incorporating insights from trench migration rates calculated for a given RPM model, even for times where hotspot trails or seismic evidence of slab material are unavailable.

For times older than 70 Ma, the distribution of trench migration rates becomes increasingly dispersed for each of the hotspot APM models. Before 70 Ma, APM models are less reliable for a number of reasons. For moving hotspot APM models, 70 Ma is close to the limit of reliability for the models of mantle flow backward advected from present day used to predict hotspot motions (Conrad and Gurnis, 2003). In addition, 70 Ma is suggested as the time at which the volcanism along the Tristan-Gough trail in the South Atlantic changed from ridge-plume interaction to an intraplate setting (O'Connor and Duncan, 1990), implying that the locations of pre-70 Ma volcanism along this chain are unlikely to be well represented either by fixed hotspots or moving hotspot models focused on deep mantle processes. In addition, global APM models can only make use of the well-sampled Pacific (Hawaii–Emperor and Louisville) trails back to ∼80 Ma, and the oldest volcanism attributed to the Réunion trail in the Indian Ocean are the ∼66 Ma Deccan Traps. Indicative of this increasing uncertainty prior 70 Ma, APM model D2012, subject to all of the above limitations, shows a focused pattern of relatively slow trench migration from 0–70 Ma, then a sharp change to more dispersed trench migration distributions for times older than 70 Ma (Fig. 3d). The Indo-Atlantic APM models and the moving hotspot reference frame T2008 show a more gradual change to more dispersed trench migration rates over the last 130 Myr (Fig. 3).

The APM model based on slab remnant matching (V2010) yields the most consistent pattern of trench migration for the last 130 Myr. For this entire time period, this APM model combined with the Seton et al. (2012) RPM model predicts a dominant trend of slow trench retreat (Fig. 3 and Table 1). For the 0–70 Ma period, the distribution of trench migration rates is similar to those predicted by hotspot APM models, but for the 70–130 Ma period APM model V2010 clearly predicts more stable trench locations. It is arguably unsurprising that an APM model derived by associating present-day fast seismic anomalies to past subduction zones performs well in relation to these criteria. However, that APM model is primarily based on only three slabs (Farallon, Mongol-Okhotsk and Aegean Tethys). The scale of uncertainties in mapping slabs from tomography means that longitudinal shifts between APM models derived from slab remnant mapping and hotspot trails are not significant for times younger than 80 Ma (van der Meer et al., 2010). The divergence for times older than 80 Ma is significant, and our results suggest that the slab remnant APM mode yields a distribution of trench migrations for the 70–130 Ma period that compares well with the distribution predicted by both this and the hotspot APM models for the 0–70 Ma period, where the hotspot models are relatively well constrained.

4.2. Geodynamic characteristics in different absolute plate motion models

Allowing for uncertainties in the RPM model, some deviations between results for different APM models are significant. While the considered APM models all predict an overall NNE motion of Africa over the last 130 Ma (Fig. 1, and mirroring the overall trend of the Tristan hotspot trail, Fig. 6), they differ in the sense of this motion over shorter (10–20 Myr) timescales. These differences are manifested in computed values for trench migration rates, NLR, and L_2-norm velocity, and provide an insight into which APM models are more geodynamically plausible.

The APM models predicting continuous NE drift of Africa (V2010, NNR; Fig. 1) give consistently low trench migration rates. In contrast, larger and more dispersed trench migration rates for other APM models typically occur during periods where the absolute motion of Africa significantly differs from this NE drift, such as the northwest motion of Africa from 100–70 Ma in APM model D2012, or the northward motion of Africa throughout the paleomagnetic models. Phases where individual APM models contain distinct spikes in NLR and L_2-norm velocity (e.g. O2005 between

50–60 Ma; D2012 between 70–80 Ma) correspond to phases where the same models also result in less favourable trench migration rates, and phases where the motion of Africa in these models deviates from a northeastwards drift (Fig. 1). These observations are unlikely to be solely due to uncertainties in the RPM model; other APM models, including alternative models based on hotspots (M1993; T2008), do not display these characteristics.

4.3. Uncertainties in the analysis

For APM models, meaningful uncertainties are difficult to calculate (O'Neill et al., 2005), particularly for models where the absolute motions of both plates and hotspots are derived using a diverse range of data and methods, for instance by combining radiometric seamount ages, relative plate motions derived from magnetic anomaly fitting, and geodynamic simulations derived using global seismic tomography models. Different studies infer different hotspot locations, resulting for example in ~180 km mismatch between inferred present-day positions for the Louisville hotspot (Wessel and Kroenke, 2008; Doubrovine et al., 2012). Uncertainties in estimated hotspot motions are similar in magnitude to hotspot motions themselves (O'Neill et al., 2005). A subset of the APM models tested here include 95% confidence estimates (O'Neill et al., 2005; Doubrovine et al., 2012) for the calculated Africa finite poles of rotation. Another model proposed a range of alternative longitudinal shifts to the position of Africa that could fit tomography constraints (van der Meer et al., 2010). For the purposes of our analysis, we have used the preferred model for each APM study considered, but note that different NLR or trench migration results could be derived within provided confidence limits.

Uncertainties in the RPM model also affect our estimates of trench kinematics and values derived from global velocity fields calculations. NLR uncertainties increase with reconstruction age as the area of the Earth for which oceanic lithosphere is no longer preserved (since it has been subsequently subducted) increases (termed 'world uncertainty' by Torsvik et al., 2010). Unlike NLR calculations, trench migration rate calculations do not require to account for the whole plate boundary system through time, but only for the locations of subduction zones. Trench migration rate calculations are relatively unaffected by uncertainties in the long plate chain from Africa to the Pacific plate and other plates within the Pacific basin, since the trench migration calculated for the subduction zones around the margins of the Pacific ocean are not dependent on the motion of the Pacific plate itself, but only of the motions of the overriding plates. For example, the trench migration along the western margins of North and South America only depends on the APM model and the relative motions between these plates and Africa.

Trench migration rate calculations depend on how well the location, timing and polarity of subduction zones are constrained. The geometries defining subduction boundaries within the Seton et al. (2012) RPM model are extrapolated from geological evidence and interpretations, and details of regional studies underpinning elements of this model are subject to debate. Competing models exist for the history of Late-Cretaceous to Cenozoic subduction within the Tethys (Zahirovic et al., 2012), southwest Pacific (Matthews et al., 2015) and western North America (Liu, 2014). Large uncertainties also exist concerning the history of intra-oceanic subduction zones within the Panthalassic Ocean. Van der Meer et al. (2012) proposed a number of subduction zones within Panthalassa, though focused on times older than those considered in this study. These subduction zones have yet to be linked to any kinematic model, so we are unable to test how they may influence trench migration calculations.

As a practical step to investigate the sensitivity of our computed trench migration results to factors not captured by formal uncertainties, we computed the statistics for models with alternative subduction histories to those presented by Seton et al. (2012) for the region east of Australia (Supplementary section A). One model features subduction with opposite polarity from 130–50 Ma, while in a second alternative scenario the subduction zone has been removed completely. The sensitivity of our global results to these regional changes is illustrated in Fig. S2; some difference is observed, but first order trends in our global results are relatively unaffected by individual, regional uncertainties in the subduction history.

4.4. Implications for future absolute plate motion models

Choosing a 'best' APM model depends on what the purpose of the model; considerations for paleoclimate modelling, where absolute paleolatitude is important, will differ from studies of geodynamics and true polar wander (e.g. Torsvik et al., 2012). Our own study was motivated for the need to model the absolute motions of plates within global simulations of mantle convection (Flament et al., 2014; Bower et al., 2015). For this application, it is preferable to avoid models where the behaviour of subduction zones is geodynamically unreasonable. In addition, it is preferable to avoid using an APM model that is closely tied to an existing geodynamic model and all the associated parameter choices (e.g. moving hotspot calculations) as an input to different geodynamic models. More generally, our results suggest that trench migration rates, and other plate velocity criteria, can provide an additional constraint both in discriminating between existing APM models and in constructing new models.

In ranking the different APM models, we draw a distinction between the periods 0–70 Ma and 70–130 Ma (Table 1). For the more recent period, hotspot and slab remnant APM models give qualitatively similar trench migration characteristics. Applying the criteria laid out by Schellart et al. (2008), model T2008 ranks the highest, giving the lowest standard deviation of trench migration rates, lowest percentage of segments retreating at more than 30 mm/yr, and the highest number of retreating segments, as well as ranking second in the other two categories. Other hotspot-based APM models, based on fixed or moving hotspots (Müller et al., 1993; O'Neill et al., 2005; Doubrovine et al., 2012) or on the slab remnants (van der Meer et al., 2010) also perform well from 0–70 Ma. For the 130–70 Ma period, the slab remnant V2010 model ranks highest in terms of trench migration criteria. Hotspot APM models perform more poorly, in accordance with the lack of constraints available for this period. APM models based on paleomagnetic data without TPW correction yield a far more dispersed pattern of trench migrations throughout the last 130 Ma, confirming our expectation that the lack of longitudinal constraint means such APM models are less suitable for the last 100 Ma.

Model V2010 appears to be an attractive option for the whole 0–130 Ma timeframe based on trench migration, and NLR. The downside to model V2010 is that it is less successful in fitting observations from hotspot trails (Table 2), though far more successful than paleomagnetic APM models without TPW correction. For the last 100 Ma, latitude in model V2010 is constrained by model O2005 to which longitudinal shifts are applied. How well would a slab-remnant APM model reconcile hotspot trails if information from the hotspot trails had not been used to create it? The poor fit between non-TPW corrected paleomagnetic APM models and observations from hotspot trails (Table 2), coupled with the large deviation in latitude (up to 10 degrees, Fig. 1) between the Early Cenozoic positions of Africa in hotspot versus non-TPW corrected paleomagnetic APM models, suggests that the success or otherwise of the V2010 model in matching hotspot trails depends on whether information from hotspot trails was used to constrain it in the first place. Our results for APM model V2010 are based

Table 2
Root-mean-square (RMS) misfits (in km) between hotspot trail predictions and dated volcanic samples along trails for a series of APM models. All values are computed using the fixed hotspot approximation and the Seton et al. (2012) RPM model with the exception of D2012*, where the values are computed using the RPM model and individual hotspot motions provided by Doubrovine et al. (2012). Bold–italic values highlight the APM model giving the lowest misfit for each trail (not including the D2012* results). Comparison between values for different trails is not meaningful, since the number of samples and maximum age along each trail varies significantly – rather, the table is intended to compare, for each trail, the ability of different APM models to match the observed sample sites.

	Tristan	St Helena	Réunion	Tasmantid	Louisville	Hawaii
M1993	***297.4***	***282.1***	327.9	171.0	415.9	665.2
O2005	316.6	486.3	342.2	213.4	398.1	579.3
T2008	325.9	409.6	***307.9***	***139.8***	349.8	499.1
D2012	445.1	429.7	479.7	145.5	***205.9***	***401.7***
T2012	636.0	749.0	758.0	424.0	631.7	1147.7
S2005	681.0	745.7	831.4	424.7	657.2	1152.2
V2010	512.7	295.6	493.9	222.6	394.2	491.6
D2012*	260.2	239.8	340.8	215.7	207.9	199.5

on their best-fitting scenario, and it is noteworthy that, owing to slab-fitting uncertainties of ∼500 km, longitudinal shifts applied to match tomography are significant for times before ∼80 Ma (van der Meer et al., 2010). For more recent times, constraints from seismic tomography could be satisfied within error using an APM model based purely on hotspots (in that case, originating from model O2005).

In defining an optimum APM model for the last 130 Ma, we prefer model T2008 over the more recent model D2012 due to the more reasonable trench migration and NLR characteristics. For the 130–70 Ma period, our analysis suggests that APM models in which Africa drifts NE during this period are most likely in terms of trench migration rates and NLR, as well as satisfying the slab remnant constraints proposed by van der Meer et al. (2010). A westward shift of ∼14 degrees at ∼130 Ma compared to the hotspot APM models falls within the range of possible fits to tomography, whilst also yielding reasonable NLR and subduction zone kinematics. Using subduction zone kinematics as part of a multi-parameter optimisation in combination with observations from age-progressive seamount trails, seismic tomography and paleomagnetism with appropriate corrections for TPW events (Steinberger and Torsvik, 2008) may provide a path to better constraining APM models. This will be the subject of a future study.

4.5. Implications for pre-Mesozoic absolute plate motion models

An important implication of this work is for the study of APMs earlier than the Cretaceous. Indeed, the notion that an optimum APM model should minimise certain parameters could be extended to construct pre-Mesozoic APMs. While the fixed hotspot approximation is often questioned (Doubrovine et al., 2012), recent studies of Paleozoic APMs propose that plume generation zones at the edge of large low shear velocity provinces have remained stable since the early Paleozoic (Torsvik et al., 2014). Within this assumption, large igneous provinces and kimberlite occurrences can provide an additional link between surface plate motions and the deep mantle, crucially providing a longitudinal constraint lacking in paleomagnetic analysis. Our analysis shows that subduction zone kinematics constitutes a constraint on APMs that is complementary to paleomagnetic data. Using both these constraints opens new opportunities for improving APM models based on paleomagnetic data alone even for times when hotspot trails or seismic tomography cannot be used. Applying the same approach further back in time depends on the ability to combine reconstructions of relative plate motions with geological evidence for the location and duration of subduction.

5. Conclusion

We find that published APM models yield strikingly different predictions of subduction zone kinematics and NLR, and that predictions made by certain models are geodynamically more plausible than others. APM models derived from hotspot trails yield reasonable distributions of trench advance and retreat for the last 70 Myr, but the distribution of trench migration velocities they predict is considerably more dispersed for the pre-70 Ma period. An APM model combining the best-fitting global hotspot APM model for the 0–70 Ma period with constraints from tomography provides a reasonable trench motion throughout the last 130 Myr. Our results suggest that the absolute motions of trenches could provide an additional constraint on APM history, both over the last 130 Ma, and for earlier times when constraints on paleo-longitude are lacking.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2015.02.026.

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