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Absolute plate motions since 130 Ma constrained by subduction zone kinematics

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A B S T R A C T

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-

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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 long-standing 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