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Global plate boundary evolution and kinematics since the late Paleozoic

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ABSTRACT

Many aspects of deep-time Earth System models, including mantle convection, paleoclimatology, paleobiogeography and the deep Earth carbon cycle, require high-resolution plate motion models that include the evolution of the mosaic of plate boundaries through time. We present the first continuous late Paleozoic to present-day global plate model with evolving plate boundaries, building on and extending two previously published models for the late Paleozoic (410–250 Ma) and Mesozoic-Cenozoic (230–0 Ma). We ensure continuity during the 250–230 Ma transition period between the two models, update the absolute reference frame of the Mesozoic-Cenozoic model and add a new Paleozoic reconstruction for the Baltica-derived Alexander Terrane, now accreted to western North America. This 410–0 Ma open access model provides a framework for deep-time whole Earth modelling and acts as a base for future extensions and refinement.

We analyse the model in terms of the number of plates, predicted plate size distribution, plate and continental root mean square (RMS) speeds, plate velocities and trench migration through time. Overall model trends share many similarities to those for recent times, which we use as a first order benchmark against which to compare the model and identify targets for future model refinement. Except for during the period ~260–160 Ma, the number of plates (16–46) and ratio of “large” plates ($\geq 10^{7.5}$ km^2) to smaller plates (~2.7–6.6) are fairly similar to present-day values (46 and 6.6, respectively), with lower values occurring during late Paleozoic assembly and growth of Pangea. This temporal pattern may also reflect difficulties in reconstructing small, now subducted oceanic plates further back in time, as well as whether a supercontinent is assembling or breaking up. During the ~260–160 Ma timeframe the model reaches a minima in the number of plates, in contrast to what we would expect during initial Pangea breakup and thus highlighting the need for refinement of the relative plate motion model. Continental and plate RMS speeds show an overall increase backwards through time from ~200 to 365 Ma, reaching a peak at 365 Ma of >14 and >16 cm/yr, respectively, compared to ~3 and ~5 cm/yr, respectively, at present-day. The median value of trench motion remains close to, yet above 0 cm/yr for most of the model timeframe, with a dominance in positive values reflecting a prevalence of trench retreat over advance. Trench advance speeds are excessive during the 370–160 Ma period, reaching more than four times that observed at present-day. Extended periods of trench advance and global continental and plate RMS speeds that far exceed present-day values warrant further investigation. Future work should test whether alternative absolute reference frames or relative motions would mitigate these high speeds, while still being consistent with geologic and geophysical observations, or alternatively focus on identifying potential driving mechanisms to account for such rapid motions.

1. Introduction

Progress in plate reconstruction modelling over the past 30 years (e.g. Scotese and McKerrow, 1990; Lithgow-Bertelloni and Richards, 1998; Scotese, 2001; Cocks and Torsvik, 2002; Stampfli and Borel, 2002; Torsvik and Cocks, 2004; Torsvik et al., 2014), coupled with technological advances in open source reconstruction software (e.g. GPlates – Boyden et al., 2011), has led to a generation of high spatial and temporal resolution models that describe the continuous evolution of whole plates, including their boundaries (Gurnis et al., 2012; Seton et al., 2012, Shephard et al., 2013; Domeier and Torsvik, 2014; Gibbons et al., 2015; Zahirovic et al., 2014; Domeier, 2016). This current generation of models is open-access (e.g. rotation and geometry files are freely available), and thus quantifiable, reproducible and adaptable. This enables testability and improvements in a community framework, and makes such models more accessible to complementary fields such as geology, geodynamics, paleobiogeography and paleoclimatology.

Plate tectonic reconstructions that incorporate evolving global plate boundaries can be integrated in numerical models of mantle convection

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as a surface boundary condition. Importantly, as they reconstruct subduction histories, that is, they predict where and when slabs entered the mantle, they enable the exploration of whole mantle evolution and the history of surface vertical motions, including dynamic and tectonic topography, over timeframes of hundreds of millions of years. Early investigations (e.g. McNamara and Zhong, 2005; Zhang et al., 2012; Flowers et al., 2012) adopted static reconstructions, with stages that were tens of millions of years long (e.g. Scotese, 2001; Lithgow-Bertelloni and Richards, 1998). Now, reconstructions with evolving time-dependent plate boundaries (resolved topologies – Gurnis et al., 2012) that enable the calculation of plate velocities and plate boundary geometries at much shorter intervals, are being used to investigate long-term mantle circulation (Bower et al., 2013; Hassan et al., 2015; Hassan et al., 2016), the degree-structure of the lower mantle (Bull et al., 2014; Zhong and Rudolph, 2015) and surface topographic evolution (Shephard et al., 2014; Flament et al., 2015).

Reconstructing subduction histories also enables the investigation of deep Earth-atmospheric relationships, such as the deep Earth carbon cycle. Subduction zone volcanism significantly affects the atmospheric carbon budget over geological time via the production of large volumes of CO_2 (Berner et al., 1983; van der Meer et al., 2014), and this addition of CO_2 to the atmosphere can be compounded when subduction zones intersect carbonate platforms leading to metamorphic decarbonation (Lee et al., 2013). It is thus useful to be able to estimate changes in subduction zone length, and associated slab flux approximations, and subduction zone location over time. Existing studies are limited and have focused on the Mesozoic (e.g. Berner et al., 1983; Lee et al., 2013; van der Meer et al., 2014) leaving room for exploration into deeper time. Estimates for changes in ridge length, particularly during major continental breakup phases are also important for studying atmospheric compositional fluctuations over deep time. Volcanism at shallow ridges, such as those that form during continental breakup, can contribute important changes to seawater chemistry, which in turn can affect ocean primary productivity and atmospheric O_2 levels (Gernon et al., 2016).

A single, global topological model with high spatio-temporal resolution that spans supercontinent assembly and dispersal, even that of the most recent supercontinent Pangea, is currently lacking, yet is essential for addressing ongoing questions about supercontinent cycles, mantle evolution, dynamic topography and the deep Earth carbon cycle over timeframes of hundreds of millions of years. Although reconstructions with resolved topologies exist for the late Paleozoic from 410 to 250 Ma (Domeier and Torsvik, 2014) and Mesozoic-Cenozoic from 230 to 0 Ma (Müller et al., 2016) or 200 to 0 Ma (Seton et al., 2012), different methodologies for connecting plate models will likely result in different velocities during the connection period that can be tens of millions of years long (Zhong and Liu, 2016) making it difficult to directly compare results from individual studies. Furthermore, access to a temporally continuous model avoids potential plate or numerical modelling artefacts arising from combining models that are not regionally consistent with each other.

To contribute to studies of long-term surface-mantle-atmospheric evolution incorporating supercontinent assembly and dispersal, we have seamlessly merged two published global plate reconstruction models with resolved topologies (Domeier and Torsvik, 2014; Müller et al., 2016), resulting in a continuous self-consistent model that spans 410 Ma to present-day. We have additionally built a late Paleozoic reconstruction for the Baltica-derived Alexander Terrane and implemented a model for the Gravina Basin during the Jurassic, both of which affect the evolution of western North America and subduction history of Panthalassa. The complete model is analysed in terms of the number of plates, predicted plate size distribution, plate and continental root mean square (RMS) speeds, plate velocities and trench migration through time, with the aim of quantifying the model, identifying major trends and isolating potential key targets for future model refinement.

2. Plate model construction

Our late Paleozoic to present-day global plate kinematic model (410–0 Ma) with continuous plate boundaries is primarily constructed from two published plate models. For the period from 410 to 250 Ma we adopt the model of Domeier and Torsvik (2014), and for the period from 230 Ma to present-day we adopt the model of Müller et al. (2016), except with an alternative absolute reference frame from 230 to 70 Ma. Hereafter we refer to these models as DT14 and M16, respectively. Both of these published models are global in spatial extent, based on the reconstruction of rigid plates (i.e. they exclude explicit modelling of deforming regions), and incorporate a dynamic network of continuous plate boundaries with resulting plate polygons.

2.1. Model construction

The construction of global plate kinematic models that incorporate a network of continuously intersecting and evolving plate boundaries is comprehensively described in the reviews of Seton et al. (2012) and Müller et al. (2016), based on the method described in Gurnis et al. (2012). More information, particularly relating to the construction and evaluation of an absolute reference frame and the incorporation of paleomagnetic constraints, can be found in Torsvik et al. (2008a) and Domeier and Torsvik (2014).

The combined plate model we present is a relative plate motion model that is ultimately tied to Earth's spin axis via an absolute reference frame. Other than Africa, the motion of any given plate is described relative to an adjacent plate numerically using a finite Euler rotation. The motion of all plates is tied, via plate motion chains, to Africa (Fig. 1a), which is traditionally considered the base of the plate 'hierarchy' due to its minimal longitudinal motion since Pangea and its position in the core of both Pangea and Gondwana (e.g. Burke and Torsvik, 2004; Torsvik et al., 2008a; Torsvik et al., 2008b). The motion of Africa is subsequently linked to the base of the mantle via a true polar wander-corrected absolute reference frame model. An exception to this is the treatment of plates in the Pacific/Panthalassic realm for times before 83 Ma, due to the lack of a shared seafloor spreading centre between the Pacific and West Antarctica, which only exists since the Late Cretaceous. For older times the Pacific/Panthalassa is surrounded by subduction zones and their constituent plates cannot be linked to a plate hierarchy with Africa at its base. As a result, plates in the Pacific/Panthalassa require a separate absolute reference frame for times older than 83 Ma, one that is also tied to the spin axis.

Both the input global reconstruction models (DT14 and M16) and the resulting 410–0 Ma model presented here were constructed using the GPlates open-source plate reconstruction software (Boyden et al., 2011; Gurnis et al., 2012). GPlates enables plates and their boundaries to be reconstructed using Euler rotation parameters. The motion of subduction zones is fixed to the motion of the overriding plate, while transforms boundaries are assigned the motion of either of their adjacent plates. The motion of mid-ocean ridges is automatically computed from that of both of their adjacent diverging plates; they are reconstructed using 'half-stage rotations' (see Seton et al., 2012). Finally, GPlates allows for the construction of resolved topologies, which are continuously-closing plate polygons constructed from the intersection of plate boundary polylines (Gurnis et al., 2012) (Fig. 1b). In addition to capturing the evolving configuration of plate boundaries, resolved topologies allow for the sampling of velocities across the entire surface of plates, not just for continents.