Supplementary information for

MIND THE UNCERTAINTY: GLOBAL PLATE MODEL CHOICE IMPACTS DEEP-TIME PALAEOBIOLOGICAL STUDIES

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SUPPLEMENTARY TEXT

METHODOLOGICAL BASIS OF GLOBAL PLATE MODELS

Global Plate Models (or Global Plate Rotation Models, GPMs) use the Euler rotation theorem to describe the motion of geometries–such as tectonic plates or geological terranes–on a sphere. A variety of tools have been developed to build global plate tectonic models. However, the most widely used tool is the cross-platform and open-source GPlates (www.gplates.org) software (Boyden et al., 2011; Müller et al., 2018) which is frequently applied to reconstruct the past geographic distribution of fossil samples using various GPMs (e.g. Allen et al., 2020; Boddy et al., 2022; Jones & Eichenseer, 2021).

A GPM is primarily made up of two key components. The first component represents the geometries that define geological boundaries, such as terranes and/or parcels of oceanic crust. GPlates stores these geometries in their present-day positions. Each geometry requires an identity number (Plate ID) and the age at which it first appears. The second component of a GPM is the motion of these geometries through time. This information is stored in a user-editable hierarchical model of finite rotations (Ross & Scotese, 1988) which describes the motion of the geometries through time. GPlates reads and interpolates data from these 'rotation files' to reconstruct the motion of geometries. The most common geometries in GPMs are 'static polygons', otherwise known as 'static plate polygons' or simply 'plate polygons'. Static polygon geometry files are typically made up of numerous polygons which represent individual tectonic plates. While these polygons can rotate across the globe, their shape does not change through time, hence the name static polygons. Each polygon within the geometry file carries a unique Plate ID and a time of appearance (and potentially disappearance) allowing tectonic plates to have an origin and ultimate demise. However, GPMs can have different static polygons (particularly between working groups) and therefore partitioning of the Earth may vary (Fig. S1). Consequently, plate IDs are unique to each static polygon file in GPMs, but they are not necessarily consistent between different GPMs. A specialised variant of plate polygons in plate tectonic modelling are known as continually-closing plate boundaries (Gurnis et al., 2012). These are time-evolving topologies of tectonic plate boundaries (rather than rotated 'static' present-day features), and they approximate the continuous evolution of plate boundaries using a set of dynamically changing plate polygons. This approach was developed to model the relationship between plate evolution and mantle dynamics. More recently, such evolving topological polygons have been expanded to capture deformation in Earth's lithosphere (Gurnis et al., 2018; Müller et al., 2019), which can be used to 'retro-deform' geological sample location (e.g. fossil localities).

Global Plate Modelling requires a 'reference frame' in which the geometries like the plate polygons move. Several reference frames have been proposed, and the types of reference frames being used are extremely important to consider. Fundamentally, 'mantle reference frames' try to isolate the plate-mantle system by eliminating the effect of the centrifugal forces due to Earth rotation on the motion of the ‘solid earth’ (lithosphere and mantle), namely true polar wander (TPW) (Steinberger & Torsvik, 2008). As both mantellic convection and TPW drive plates motion, removing TPW allows isolation of the plate-mantle system and in turn investigation of the motion of the Earth’s outer shell relative to the mantle. For that quality, they are mostly used by the geodynamics and tectonics community. However, removing TPW can have a negative impact upon the reconstruction of palaeocoordinates (i.e. for fossil occurrences or geological samples) (Seton et al., 2023). Therefore, the use of GPMs for palaeoclimatic or palaeobiological studies should carefully consider whether a mantle reference frame is appropriate. For palaeoclimatological and palaeobiological applications, a pure palaeomagnetic reference frame is likely to be more appropriate as it does not eliminate the effects of TPW and is therefore more likely to report true geographic palaeolatitudes.

To constrain the motion of tectonic plates, reference frames are compiling geological data. In particular, palaeolatitudes are robustly estimated using the palaeomagnetic record (i.e. from the inclination of magnetic minerals) (e.g. Beck, 1988; Merdith et al., 2021; Voo, 1993), but due to the radial symmetry of Earth’s magnetic field, palaeomagnetic data cannot be used to assess palaeolongitudes. Nevertheless, palaeolongitudinal positioning is possible in a mantle reference frame where a comprehensive set of hot spot tracks can be used to infer the absolute motion of tectonic plates with respect to the base of the mantle (assuming that mantle plumes do not have substantial movement or deflection). Two types of hotspot reference frames have been developed, ones that assume ‘fixed hotspots’ that do not move (e.g. Müller et al., 1993; Torsvik et al., 2008), and others that incorporate ‘moving hotspots’ to optimise the fits between hotspot tracks on plates and the source of the hotspots (e.g. O’Neill et al., 2005; Torsvik et al., 2008). The fixed-hotspot reference frame combines palaeomagnetic data with the positional information derived from volcanic hotspots tracks (Müller et al., 1993; Scotese, 2021). However, due the loss of oceanic crust, useful hotspot tracks only extend back until the Early Jurassic. Although (Torsvik et al., 2008) proposed a unifying reference frame constraining palaeolongitude over the last 320 Ma, it is not widely used (Boddy et al., 2022; Merdith et al., 2021).

Though there is currently no method to adequately constrain longitude for intervals prior to 200 Ma, several approaches have been taken to constrain longitudinal positions. A common solution is the ‘Africa-fixed’ reference frame (Scotese et al., 1988; Torsvik & Cocks, 2016). This approach affixes Africa to the prime meridian (Scotese, 2021) or to a set of active hotspots that surround Africa (Large Low Shear-wave Velocity Provinces) (Torsvik & Cocks, 2016). In these reference frames, Africa remains near the centre of the map, relative longitudinal motions between the plates are preserved and erratic shifts in longitude are eliminated. Another approach is to apply kinematic constraints to minimise trench advance and net rotation, and derive a mantle reference frame that also infers palaeolongitude (Müller et al., 2019, 2022; Tetley et al., 2019).

GPMs are often constructed to address specific applications, such as using mantle reference frames to model mantle convection and isolate the plate-mantle system. However, for the palaeoclimatic and palaeobiological communities, it is crucial to understand what absolute reference frame is used as it may impact upon their reconstructions and subsequent conclusions. In addition to 'rotation files', which describe the relative and absolute plate motion paths, the subdivision of Earth's crust into terranes (or blocks) can also introduce differences in the reconstruction of palaeocoordinates. In most cases, the source of this uncertainty is from varying interpretations of suture zones, where the geological boundaries are typically complex due to prolonged or multiple deformation events. As a result, one should evaluate the impact of GPM choice in relation to their data and understand that each variant carries spatially and temporally evolving uncertainties.

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SUPPLEMENTARY FIGURES

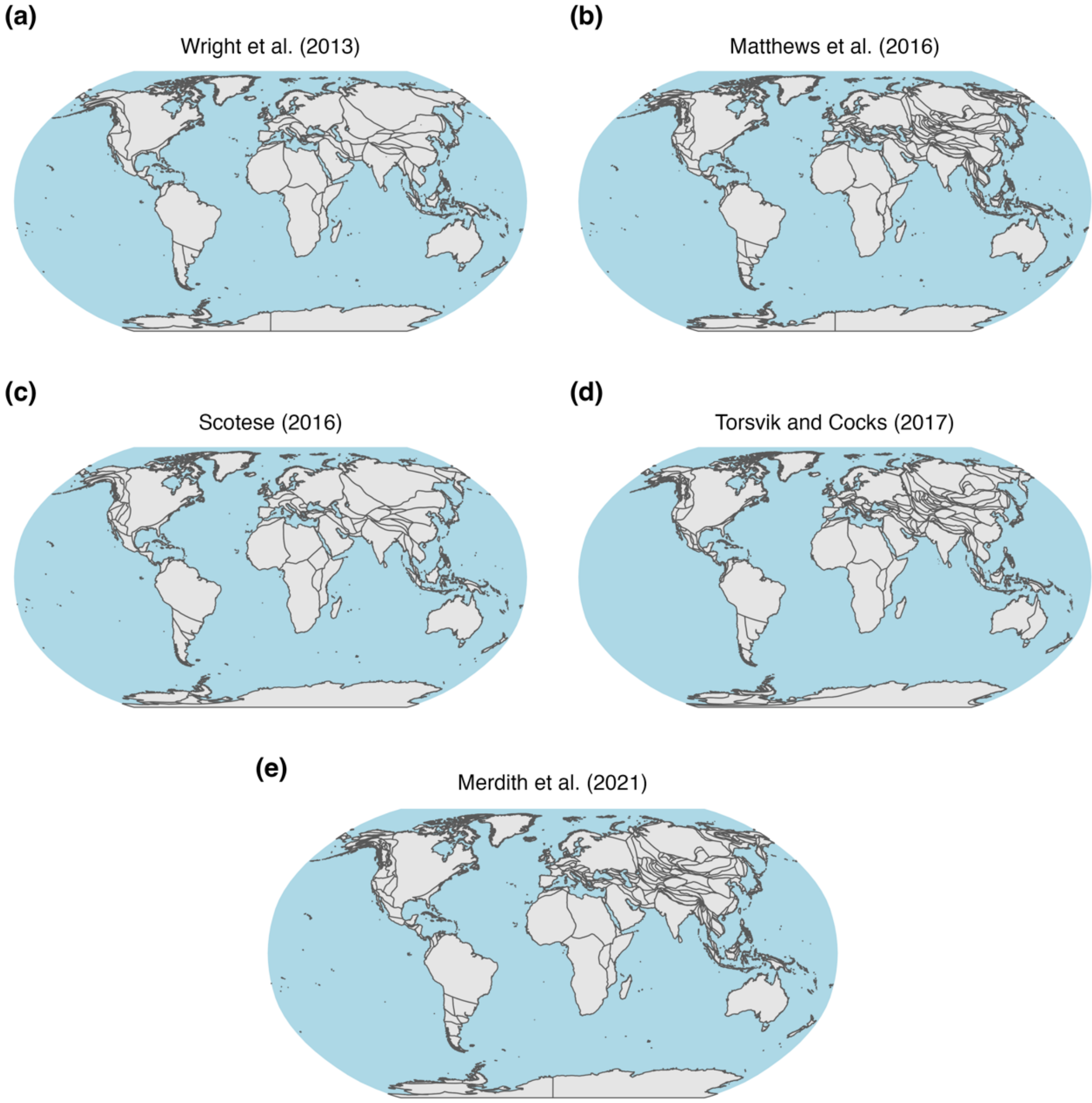

Figure S1: Continental plate polygons for Global Plate Models used in this study. Note: Global Plate Models partition continental plate polygons differently, including where polygons are partitioned, and how many partitions are present. Maps are presented in the Robinson projection (ESRI:54030).

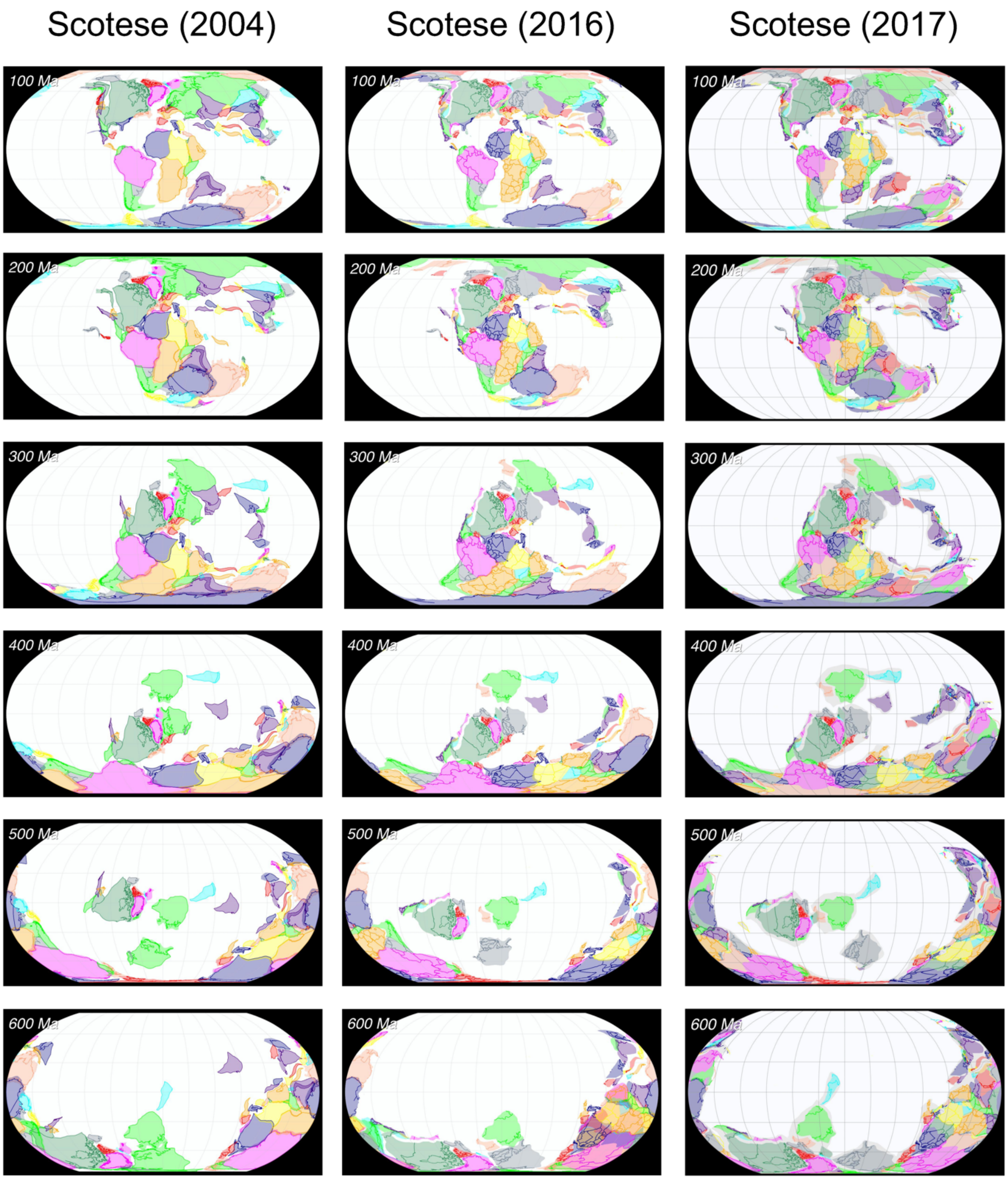

Figure S2: Evolution of the Scotese Global Plate Model (2004–2017). Small changes occur in the location of the ‘core’ continents. Major changes occur in the placement of N. China, S. China, Cimmeria, and the exotic terranes of western North America. The time range of the models has also evolved (though not fully depicted here), with Scotese (2004) ranging from 0–750 Ma, Scotese (2016) from 0–1100 Ma, and Scotese (2017) from 0–1500 Ma. Maps are presented in the Robinson projection (ESRI:54030).

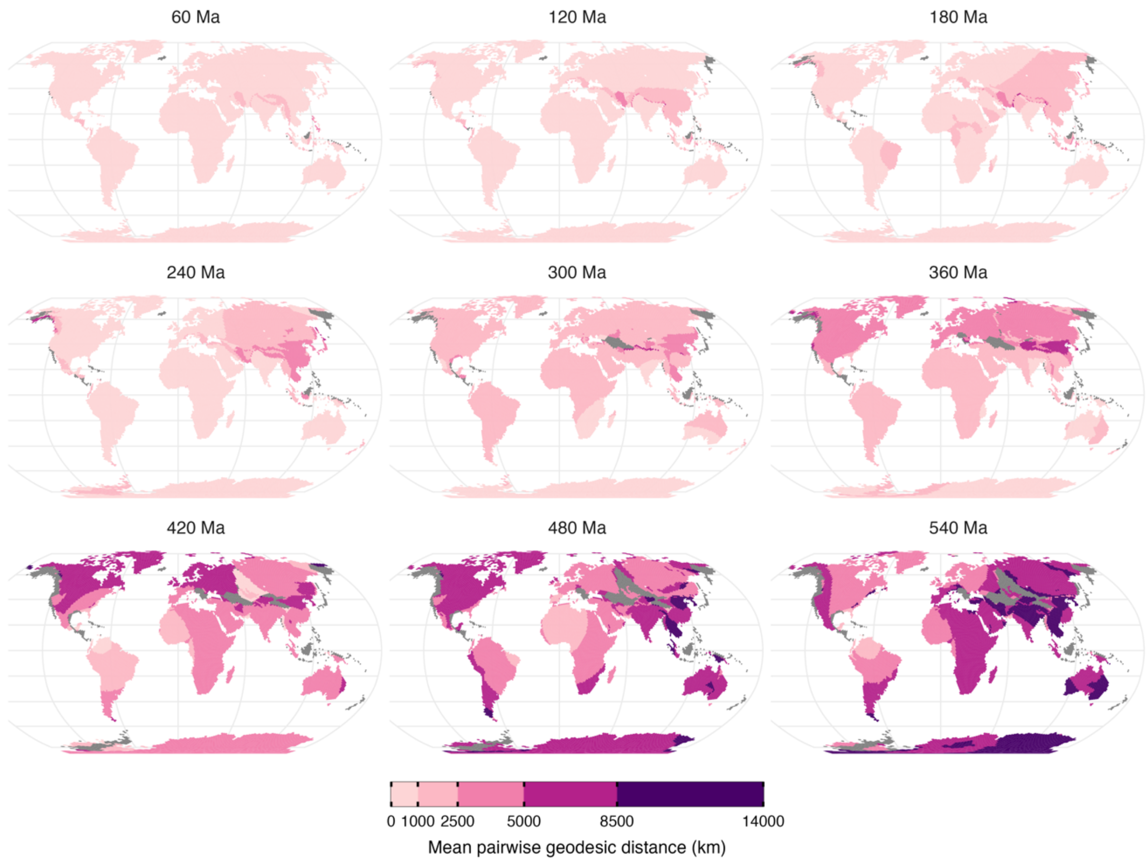

Figure S3. Categorised maps of the mean pairwise geodesic distance between reconstructed palaeocoordinates of cell centroids from Global Plate Models. Values are mapped onto a present-day map with darker shades indicating greater geographic distance between palaeocoordinates. Grey cells denote areas where palaeocoordinates could not be reconstructed at time of reconstruction for cell centroids by at least two models. Maps are presented in the Robinson projection (ESRI:54030).

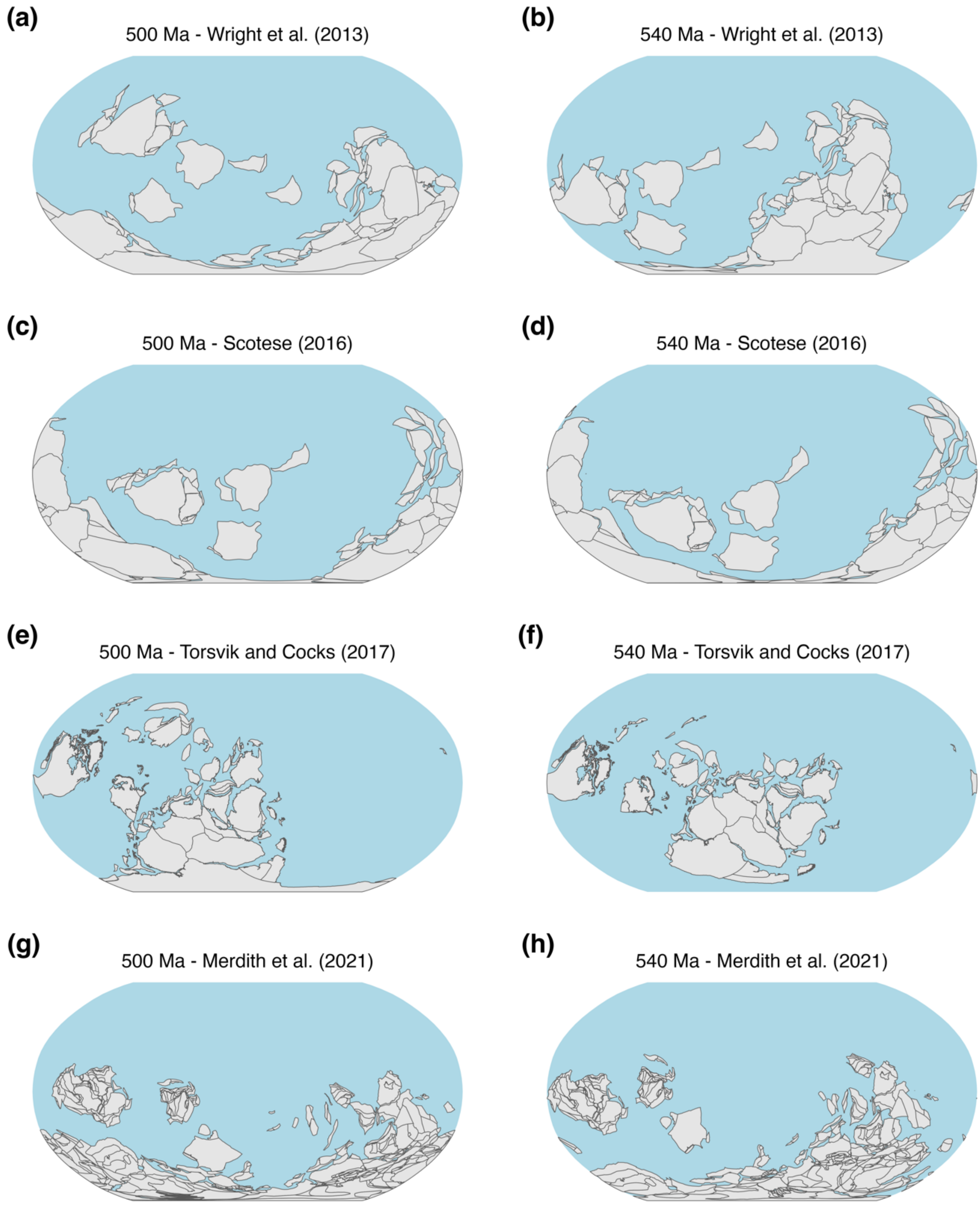

Figure S4: Reconstructed continental areas of the early and late Cambrian according to different Global Plate Models: WR13 (a, b), SC16 (c, d), TC17 (e, f) and ME21 (g, h). The left-hand side of the panel depicts palaeogeographic reconstructions of the Earth at 500 Ma (early Cambrian). The right-hand side of the panel depicts palaeogeographic reconstructions of the Earth at 540 Ma (late Cambrian). The MA16 Global Plate Model is not depicted here as the Cambrian is not within its temporal coverage. Maps are presented in the Robinson projection (ESRI:54030).

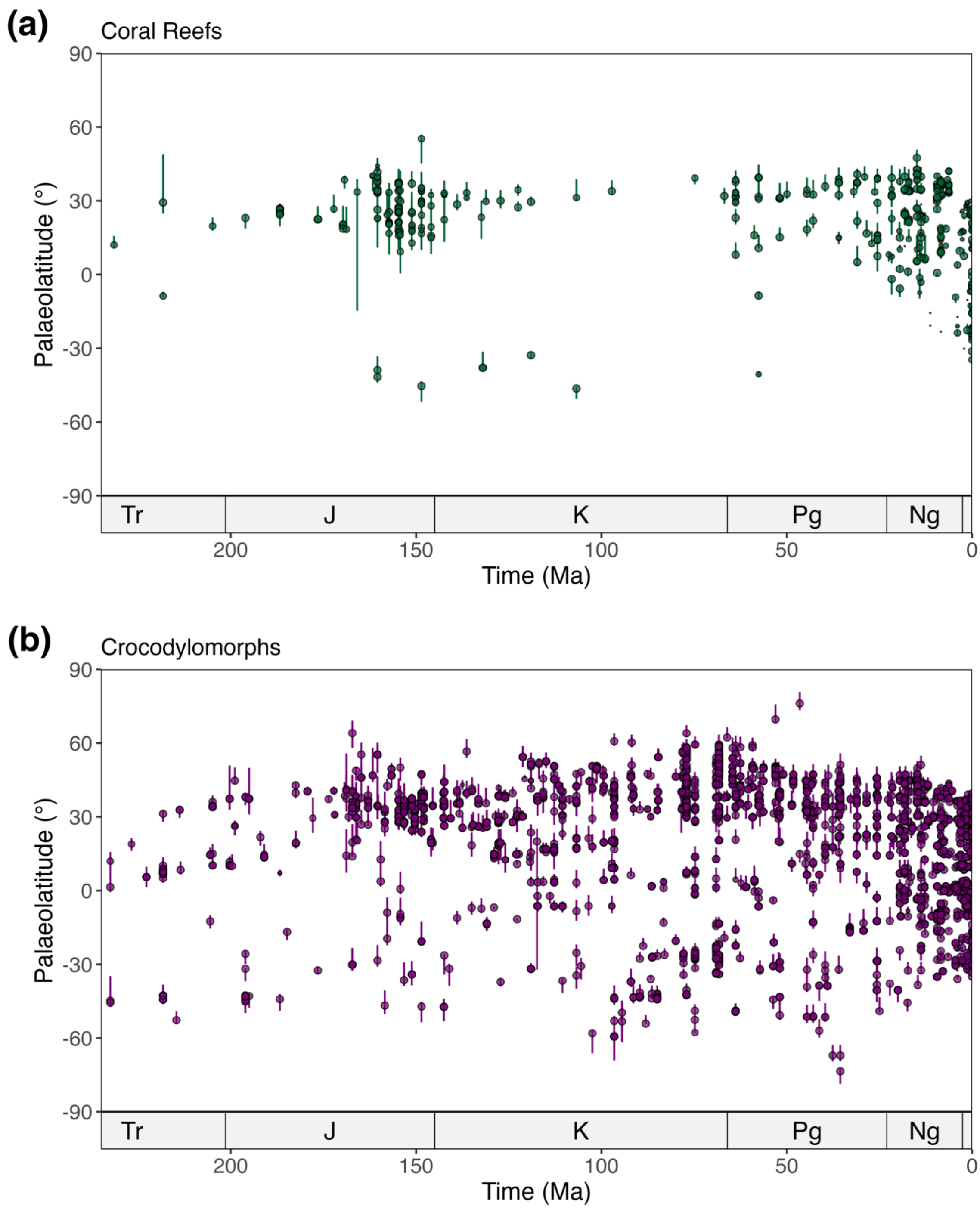

Figure S5: Palaeolatitudinal reconstruction of fossil coral reefs (a) and terrestrial crocodylomorphs (b) according to the five Global Plate Models used in this study. Each point represents the median of the palaeolatitude estimate for an occurrence. The size of the points is proportional to the logarithm of the number of models palaeocoordinates could be reconstructed from (n = 1 to 5). Each bars depict the minimum and maximum palaeolatitudinal estimate for an occurrence. Pearson's correlation tests showed significant positive relations between the age of reconstruction and average range of palaeolatitudinal estimates per time interval (R = 0.33–0.49; $P < 0.001$).