nature reviews earth & environment
https://doi.org/10.1038/s43017-022-00384-8

Technical review

Check for updates

Deconstructing plate tectonic reconstructions

In the format provided by the authors and unedited

Deconstructing plate tectonic reconstructions

Seton, Maria[1†], Williams, Simon E.[2,3], Domeier, Mathew[4], Collins, Alan S.[5], Sigloch, Karin[6,7]

[1] EarthByte Group, School of Geosciences, University of Sydney, Sydney, NSW, Australia

[2] State Key Laboratory of Continental Dynamics, Northwest University, Xi'an, China

[3] Institute of Marine and Antarctic Studies, University of Tasmania, Hobart, TAS, Australia

[4] Centre for Earth Evolution and Dynamics, University of Oslo, Oslo, Norway

[5] Tectonics and Earth Systems Group (TES), Department of Earth Sciences, University of Adelaide, Adelaide, SA, Australia

[6] Université Côte d'Azur, Géoazur, CNRS, Sophia Antipolis Cedex, France

[7] Department of Earth Sciences, University of Oxford, Oxford, UK

† email: maria.seton@sydney.edu.au

Supplementary Information

Supplementary Note

Basics of plate motions

The displacement of any object across the surface of a sphere can be described by a finite rotation, and so fundamentally, all plate reconstructions can be considered a time-dependent sequence of finite rotations (often called 'Euler poles' in the plate tectonic literature, even though finite rotations specify both a pole of rotation and an angular displacement about the pole). In plate tectonic modelling, two flavors of finite rotations are distinguished: 'stage poles' and 'total reconstruction poles'. Stage poles define the rotation of an object between any two discrete times, whereas a total reconstruction pole is the sum of a series of stage poles describing the motion of an object between present-day and some time in the past. Total reconstruction poles therefore describe the 'net displacement' of an object between present-day and some time in the past. Finite rotations (as either stage poles or total reconstruction poles) can be used to describe either the motion of one mobile object (such as a plate) relative to another--reflecting 'relative plate motion' (RPM)--or relative to some 'fixed' system of reference that allows the definition of so-called 'absolute plate motion' (APM). A determination of South America's motion relative to Africa is an example of RPM (Supplementary Figure 1), whereas the determination of Africa's motion relative to hotspot trails (generated by plumes from the mantle) is an example of APM (Supplementary Figure 1).

It is important to recognize that the enterprise of building rigid plate reconstructions is tantamount to discovering and collating finite rotations that reflect APMs or RPMs. These can be estimated (either quantitatively or qualitatively) from a wide variety of observational data and inferential constraints (see main text). In the case of tomotectonic models, for example, we seek a series of finite rotations that restore surface records of past subduction above the fast seismic anomalies in the mantle that are thought to reflect the locations of their corresponding paleo-subduction zones through time. For deforming models, finite rotations alone cannot describe continuous deformation fields, but they can represent the motion history of individual elements within deforming regions (see[1] and main text).

Most of the finite rotations defined in global Mesozoic-Cenozoic plate tectonic models describe RPMs within a structured plate hierarchical system tied to an absolute reference frame (Box 1 and Supplementary Figure 2). In contrast, pre-Mesozoic models tend to link most plates directly to the Earth's spin-axis since they are first and foremost constrained by palaeomagnetic data (Supplementary Figure 2). Further elaborations of plate motions in the context of plate reconstructions can be found in[2,3].

More on absolute reference frames

Global plate reconstruction models are built with an embedded absolute reference frame (e.g. the models ported with *GPlates*). The issue of which absolute reference frame to use is only important for studies where the absolute position of a feature on the surface of the Earth is required. A summary of the various types of absolute reference frames can be found in Box 1 in the main text and in[4]. All methods to build APM models rely on simplifying assumptions, such as hotspot fixity, the GAD or the adoption of geodynamic principles (see main text).

For reconstructions of relatively recent times (e.g. since Pangea breakup), various global models have been proposed that focus on a single approach or line of evidence (e.g. hotspot trails) to define their reference system. For deeper time, it is more common to use hybrid approaches whereby the overall APM model relies on different methods for different time periods. For example, a hybrid reference frame could combine hotspot models for the Cretaceous to present with models based on LIPs and kimberlites being linked to PGZs or paleomagnetics corrected for true polar wander for times before the oldest preserved hotspot trails.

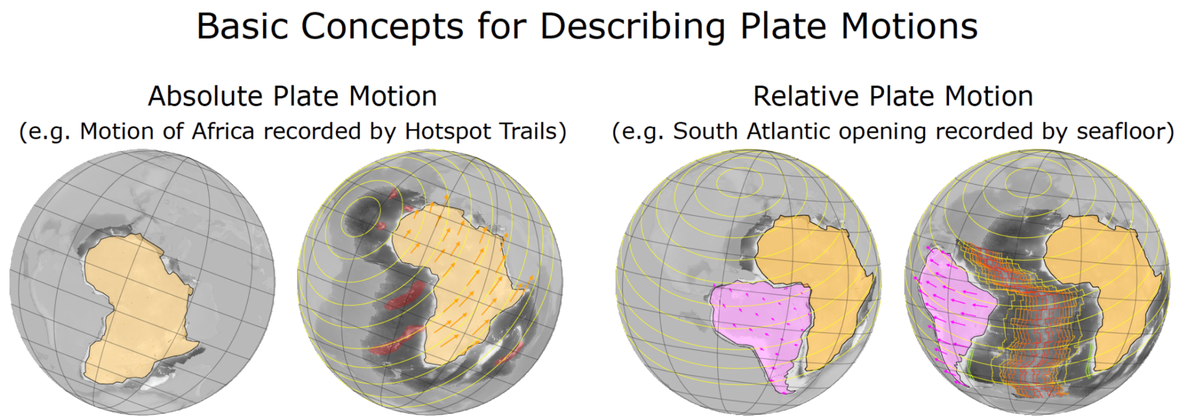
The reference frame upon which any given global reconstruction model is built should be documented both in the original study and within the rotation file of the associated model. In the example of GPlates, by default, any model loaded into the software will use a plate identification number of '0' as the 'Anchor Plate', and in most cases this will imply some kind of reference frame as documented in the original study. It is worth keeping in mind that the 'Anchor Plate' can be set to any plate within the hierarchy - this may be the best option when the focus of a study is on regional tectonics where the absolute position is less significant.

Reconstructions ported with GPlates

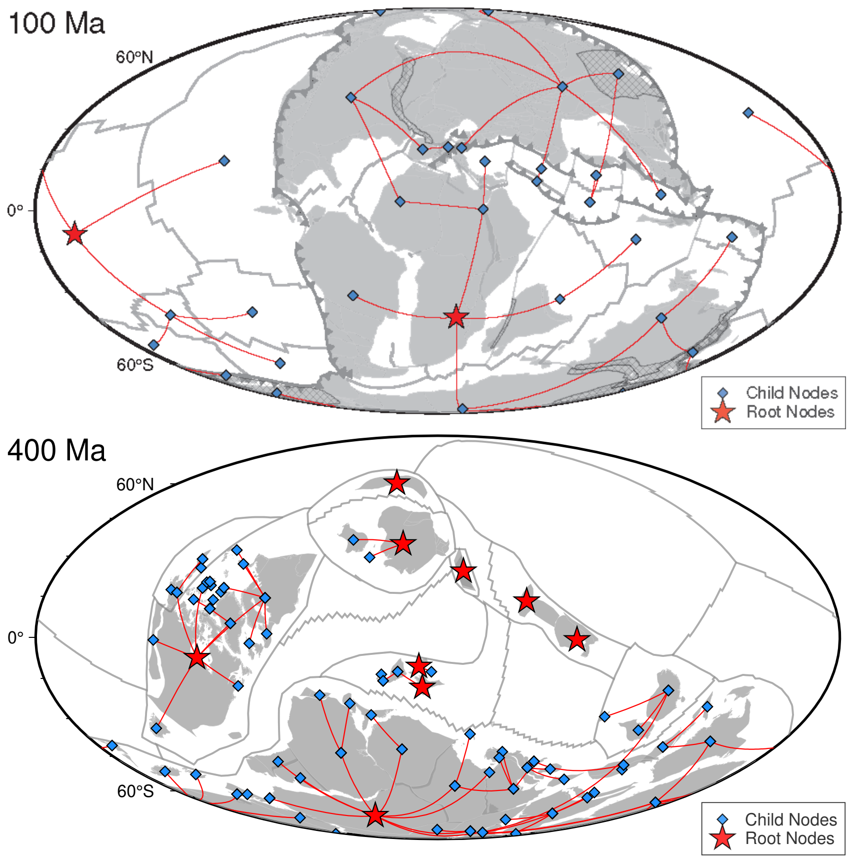
Over the years, many papers have referred to plate reconstruction models that are ported with GPlates as "the GPlates plate model". There is no such thing as "the GPlates plate model". GPlates is just software. There are stand-alone, peer-reviewed and well-documented global reconstruction models provided as sample data when GPlates is downloaded. The default plate model that is ported with GPlates is often updated with every new release. Keeping accurate records of the plate model that is being used and assessing its suitability for the particular research question being addressed is good practice.

Another important note is that global plate reconstructions are compilations that build on many regional studies from numerous publications. These global compilations (like the ones ported with GPlates) include line-by-line citations (with doi) for all the rotations that are included in the file. For global or large-scale regional studies or ones that rely on a plate circuit, referencing the global model is the appropriate approach. However, for studies that only use a small subset of the rotation file (e.g. the relative motion between South America and Africa, Supplementary Figure 1), it is best practice to acknowledge the specific rotations for that plate pair rather than referencing the global compilation. For a description of the GPlates rotation file, see[5].

Supplementary Figures



Supplementary Figure 1: The basic concepts for describing plate motions. For the absolute motion example, the plot shows concentric small circles drawn around the pole of rotation describing the average absolute motion of Africa relative to the mantle over the past 130 Myr, as deduced from hotspot trails. Velocity vectors for this average motion are parallel to these small circles. Red polygons broadly outline the hotspot trails of age-progressive volcanism formed as the African plate moved over hotspots assumed to have remained roughly fixed in the underlying mantle. For the relative motion example, the motion of South America is shown relative to Africa, which is held in a fixed position. This relative motion is determined from the record of seafloor spreading preserved in the South Atlantic ocean as marine magnetic anomalies, which can be converted into isochrons (lines of equal seafloor age) shown as coloured lines from old (light green) to young (red). Reconstructing the relative motion of the Africa-South America plate pair involves fitting together each isochron from one side of the ocean with the isochron of the same age from the opposite side. This procedure results in poles of rotation that describe the relative motion between the plates (independent of the absolute motion of either plate).



Supplementary Figure 2: Demonstration of two alternative plate hierarchies. During the Cenozoic-Mesozoic (as depicted in the 100 Ma reconstruction), the plate hierarchy is built with Africa as the root node (or parent plate; red star), that in turn is tied to an APM model. Africa is often chosen as the root node because it has been relatively stationary since Pangea breakup, though for older times the same rationale would not apply. In this illustration, the hierarchy is depicted for the topological plate polygons only. Child nodes (blue diamonds) are all ultimately linked back to the root plate. RPMs between plate pairs are depicted via the red lines connecting each node (or plate). The exception is the Pacific plate, which cannot be linked to Africa for times prior to 83 Ma and requires its own APM model (in this case based on Pacific hotspots) from which the proto-Pacific plates (e.g. Izanagi, Farallon, Phoenix) hang. For older times, as reflected in the 400 Ma reconstruction, the plate hierarchy uses many more root plates or nodes, each of which are independently tied to a common APM reference frame. The difference in this hierarchical structure reflects the fact that RPMs are much more difficult to establish in pre-Jurassic time, as their records in the past oceanic basins have been recycled. Plate boundaries are plotted as grey lines, with subduction zones shown with teeth indicating polarity. Grey polygons denote continental areas.

References

1. Gurnis, M. *et al.* Global tectonic reconstructions with continuously deforming and evolving rigid plates. *Comput. Geosci.* **116**, 32–41 (2018).
2. Cox, A. & Hart, R. B. *Plate tectonics: How it works*. (John Wiley & Sons, 1991).
3. Wessel, P. & Müller, R. D. Plate tectonics. *Treatise Geophys.* **6**, 49–98 (2007).
4. Torsvik, T. H., Müller, R. D., Van der Voo, R., Steinberger, B. & Gaina, C. Global plate motion frames: toward a unified model. *Rev. Geophys.* **46**, (2008).
5. Qin, X. *et al.* The GPlates geological information model and markup language. *Geosci. Instrum. Methods Data Syst.* **1**, 111–134 (2012).