Plotting on Possible Earths:

a palaeontologist's guide to plate reconstructions and palaeogeography

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Abstract

In the past decade, using plate tectonic models has become a cornerstone of quantitative palaeobiology. Despite their broad distribution, frequent use and the increasing number of available global plate models (GPMs) there is little communication between palaeobiologists and model developers, which limits not only their critical use for palaeontological data analysis, but also the responsible integration of fossil data into palaeogeographic reconstructions. Focussing on GPM application in quantitative palaeobiology, in this introductory chapter we revisit the use of basic features of GPMs, the types of data integrated in them, highlight some technical aspects of plate tectonic reconstructions and try to provide guidelines to using the available resources. We introduce practical suggestions for model selection and usage, discuss consequences of plate model differences, and propose practices for community-driven data refinement. We highlight best practices for using GPMs in palaeontological research focussing on the importance of reproducibility and data principles. Through this synthesis, we aim to facilitate more robust and reproducible applications of tectonic models in palaeontology, and to support a broader, interdisciplinary dialogue around the role of Earth's dynamic surface in shaping the history of life.

1. Introduction

The fossil record provides empirical evidence of biological evolution, climate-driven range shifts, extinction events, and recoveries, offering insight into the dynamic interplay between biota and Earth's changing environments. Palaeobiologists rely on reconstructed palaeogeographies to study these patterns, with global plate models (GPMs) forming a foundation for understanding the shifting arrangement of the Earth's surface through geological time. GPMs use geological and geophysical data to trace the motion of tectonic plates, enabling the dynamic reconstruction of past positions of continents, geography, and climate systems. These models are becoming indispensable for studies of deep-time biodiversity, as they provide spatio-temporal and environmental contexts for understanding ecological and evolutionary processes (Fig. 1).

Each model represents a distinct and plausible version of Earth history. As the number and accessibility of GPMs grow, users are increasingly confronted with the variability amongst

models. Differences between GPMs have been shown to generally increase with increasing reconstruction age (Buffan et al., 2023), reflecting variation in data availability and integration strategies, for example, the treatment of plume generation zones and Large Low Shear Velocity Provinces (Section 2.3; Vérard 2019; Seton et al., 2023). The activity in the GPM development landscape creates a need for best practices in their application by users, as well as methods to identify how differences between models propagate into biological interpretations. As the variation among possible Earths particularly affects the Paleozoic, in this chapter of *Geography and Life before Pangea*, we outline key aspects of GPM construction, clarify underlying assumptions, and highlight factors critical for reconstructing fossil localities, particularly in climatically sensitive analyses.

1.1. The landscape of GPMs

Plate tectonics is the unifying theory that explains Earth's geological processes, from its core to its crust, shaping both past and future landscapes. It describes the interactions between the mantle, lithosphere, hydrosphere, atmosphere, and biosphere, forming the foundation for integrated deep-time Earth System Modelling (ESM; Fig. 2). In reconstructing past environments, GPMs, being digital representations of different tectonic scenarios through time, provide a critical framework for deep-time biogeographic analyses, which suggest that climate and geography drove species distributions at regional and global scales (Blois et al., 2025; Kocsis et al., 2018b; Powell, 2007; Saupe, 2023).

The proliferation of GPMs has expanded opportunities in biogeography, macroevolution, and palaeoclimate research (Brownstein et al., 2023; Malanoski et al., 2024; Marcilly et al., 2025; Powell 2009). Plate motions associated with supercontinent cycles have profoundly influenced ocean circulation, atmospheric chemistry, sedimentation, and biodiversity patterns (Cao et al., 2019; Malanoski et al., 2026; Seton et al., 2023; Wong Hearing et al., 2021). The emergence of open-source tools such as *GPlates* (Müller et al., 2018) has transformed the field, enabling non-specialists, including palaeontologists, to access, visualise, and integrate tectonic reconstructions into analytical workflows (see Harper et al., this volume).

However, the abundance of resources has also introduced challenges for prospective users. Each model reflects a unique (but often interrelated) scenario for plate motions, tectonic partitioning, and a different subset of incorporated data, which can significantly alter palaeogeographic and climatic reconstructions and, consequently, biological interpretations (Buffan et al., 2023; Leonard et al., 2025; Wong Hearing et al., 2021). Differences in transparency, documentation, and data provenance further complicate reproducibility and cross-study comparison (Chang et al., 2024). Consequently, there is a risk that users treat a single model as authoritative without considering alternative tectonic scenarios or the variation inherent in deep-time reconstructions (Buffan et al., 2023; Torsvik et al., 2025). At the same time, variability among models offers an opportunity to test the robustness of palaeobiological interpretations, explore alternative hypotheses, and identify patterns consistent across multiple reconstructions. Improved communication between model developers and users, and the establishment of community standards are therefore increasingly important.

1.2. GPMs in palaeobiology

In palaeobiology, GPMs provide a framework for embedding fossil occurrences within a coherent spatiotemporal reconstruction of Earth (Fig. 1). This enables analyses of range size (Chiarenza et al., 2023; Saupe et al., 2015), dispersal pathways and connectivity (Brocklehurst et al., 2018; Lam et al., 2021; Moreno et al., 2024; Young 2010), biogeographic structure (Blois et al., 2025; Dowding and Ebach, 2018; Kocsis et al., 2018a; Penn-Clarke and Harper 2023), and extinction dynamics (Malanoski et al., 2024; 2026; Penn et al., 2018; Saupe et al., 2020). GPMs function as integrative hypotheses, translating geological, geophysical, and geodynamic constraints into spatial scaffolds onto which fossil data are projected. Biological conclusions are therefore conditional on the structure of the model, including its temporal resolution, reference frame, and internal treatment of data (see Dowding et al., this volume). The palaeogeography used in any analysis is one of several plausible scenarios defined by a given model (Vérard, 2019; Seton et al., 2023)—presenting a different possible Earth on which we can plot.

When a fossil occurrence is adapted to a GPM, it is assigned to a plate within the tectonic partitioning of the model (e.g. *plateID 801*-Australia; `PALEOMAP`) based on its present-day coordinates. It is then reconstructed to a **target age** using the model's plate rotations and topology, within a specified reference frame. Provided the fossil datum's age (derived from chronostratigraphy) falls within the temporal duration of the plate (Textbox 1), it inherits the kinematic history of that plate, including changes in latitude, longitude, and orientation.

Recognising GPMs as shared digital objects between palaeontology and other disciplines of Earth system science highlights both their utility and limitations for users, and opportunities for palaeontologists to contribute to GPM development. For users, palaeobiological analyses rely on GPMs as external spatial frameworks rather than co-evolving systems. This distinction underscores the conceptual difference between working on reconstructed biogeography (wherein GPMs and ESMs are used to interpret fossil data) and modern-day fossil biogeography (wherein modern-day locations are used; see Dowding et al., this volume), and the conditional nature of biological inferences drawn from any single palaeogeographic model (See Fig. 1; Textbox 1) .

2. Where do different GPMs come from?

In palaeontology (and aligned fields) 'models' can be any cognitive representations of reality, but they most frequently relate to probabilistic-statistical frameworks or mechanistic data generators. However, within the hypotheses of possible past Earths, a GPM can be defined as a function that renders past positions (palaeocoordinates) at a specified time (target age) from present-day locations (geographic coordinates).

Numerous researchers work on the development of reconstructive models and the products derived from them (Fig. 2) and each returns internally consistent and precise hypotheses of plate topology, rotation, and arrangement (See Section 2.2). Variation and consensus between models reflect both the scientific interest of the developer and the availability, integration and expert interpretation of data and geodynamic parameters and processes. The majority of GPMs

are not probabilistic models; i.e. statistical frameworks that incorporate uncertainty and randomness to predict outcomes as likelihoods rather than certainties. They are internally consistent functional hypotheses and as a consequence, discussions of 'uncertainty' or the formal quantification of cross-model variation relevant to palaeontologists are best addressed through sensitivity analyses.

2.1. Types of global plate models

GPMs vary in structure depending on their scientific objectives and data inputs leading to four different kinds of GPMs (Seton et al., 2023). **Continental drift models** reconstruct continental positions using geological correlations and palaeomagnetic data (e.g. Müller et al., 2016), whereas **plate tectonic models** incorporate dynamic processes such as plate boundary evolution (e.g. Merdith et al., 2021).

Tomotectonic models reconstruct plate motions using seismic tomography to align the history of subduction zones with subducted slab material to ~200-300 Ma (e.g. Clennett et al., 2020). These models are focussed on mantle dynamics and inherently use a mantle reference frame. While powerful for deep mantle studies, they are less directly relevant to surface ecosystems and biogeography. **Deforming Plate models** extend plate-focused models by incorporating continuous deformation within plate interiors (e.g. mountain belts or rift zones; Müller et al., 2019).

Models can use either of these two reference frames for inferring the positions of terranes:

- **Palaeomagnetic reference frame (PMRF):** tied to Earth's spin axis (geographic poles) given that the time-averaged magnetic field aligns with the planet's rotation.
- **Mantle reference frame (MRF):** tied to mantle structures such as hotspots or subducted slabs.

A complete model of all tectonically relevant knowledge would, in principle, produce a single coherent reconstruction of past geography. In practice, GPMs are developed to model different processes that lead to diverging reconstructions. The different model types and reference frames reflect the deliberate prioritisation in researching different aspects of the Earth system. **Currently, palaeontologists and those working with climatically sensitive data should only use models within a palaeomagnetic reference frame (see Section 2.1.1).** The current volume is focussed on Paleozoic life and geography, consequently we hereafter limit discussion to the most used tectonic and drift models within a PMRF: `PALEOMAP` (Scotese, 2016; Scotese and Wright, 2018), `MERDITH2021` (Merdith et al., 2021) and `TorsvikCocks17` (Torsvik and Cocks, 2017).

2.2. Palaeomagnetic reference frames and climate

Plate motions are primarily described in two ways: absolute and relative plate motions. **Absolute plate motions** describe how plates move relative to a fixed reference system tied to 'stable' features of the Earth itself, such as mantle structures (e.g. hotspots and LLSVPs) or the

spin axis. **Relative plate motions** describe how plates move with respect to one another (Torsvik and Cocks, 2017). Relative plate motions are transformed into an absolute reference frame (whether MRF or PMRF) by anchoring a global, interconnected network of plate movements to a fixed feature such as the spin axis and mantle structure (e.g. hotspots; Doubrovine et al., 2012). This process, often referred to as absolute plate motion modelling, requires calculating the motion of one "anchor" plate relative to a hotspot for example and then adding that plate's relative motion to the rest of the network (Doubrovine et al., 2012). The **palaeomagnetic reference frame (PMRF)** reconstructs absolute plate motions relative to the Earth's spin axis.

For the Paleozoic, palaeomagnetic poles represent the most robust quantitative constraints available for reconstructing plate motions: they are estimates of the position of Earth's magnetic north or south pole, derived from analysing the magnetic signature "frozen" into rocks at the time of their formation, e.g. through thermoremanent magnetisation (Torsvik and Cocks, 2017; van der Boon et al., 2022; van der Boon and Dowding, this volume). From these palaeomagnetic data, palaeolatitude and plate orientation can be determined with reasonable precision. However, longitude cannot be constrained using palaeomagnetic data alone due to the radial symmetry of the **Geocentric Axial Dipole**.

The most reliable palaeomagnetic data are typically derived from igneous rocks, but these become increasingly scarce beyond ~225 Ma, corresponding to the maximum age of preserved oceanic crust (van der Boon et al., 2022; Seton et al., 2023). Maintaining the reconstructions' consistency with the spin axis is crucial for paleontological applications. The spin axis governs the distribution of incoming solar radiation hitting Earth's surface, meaning that latitude and thus climate, seasonality, and biodiversity patterns are fundamentally linked to it (Leonard et al., 2025). As a result, PMRFs provide the closest approximation for the relationships between absolute latitude and its environmental consequences.

Further, a key advantage of a PMRF for palaeobiological studies is that it preserves **True Polar Wander (TPW)**, the wholesale reorientation of the solid Earth relative to the spin axis (Evans, 2003; Torsvik et al., 2012, 2014; Leonard et al., 2025). In simple terms, TPW reflects a collective shift of the entire solid Earth, superimposed on ongoing plate interactions, leading to substantial latitudinal displacement through time. For some geodynamic applications, however, it is necessary to remove the TPW signal and adopt a mantle reference frame. This correction typically shifts reconstructed palaeolatitudes by ~10–12° in the Palaeozoic relative to PMRF-based reconstructions (Müller et al., 2022; Seton et al., 2023; Vérard, 2019). Such differences are highly consequential for palaeontological studies: a latitudinal shift of this magnitude can significantly alter interpretations of climate, environmental gradients, and biodiversity patterns (Leonard et al., 2025; Wong Hearing et al., 2021).

Consequently, because PMRFs are anchored to the spin axis and retain TPW, they remain the only appropriate reference frame for deep-time palaeontological applications and should be used as the default for contextualising fossil distributions.

2.3. Building a plate model

GPMs are primarily built backwards from the modern into deep time (except, for example, Li et al., 2008). To reconstruct the Earth as it was 500 Million years ago, the vast majority of models begin with reconstructing the immediate past. When reconstructing into the past, each older iteration of the model has to line up with the previously-reconstructed, younger times (backward compatibility of deep time to the present). Consequently, as the reconstruction of ever older times is attempted, the declining availability of data is compounded with the aggregated impacts of decisions about reconstructing younger times (Seton et al., 2023; Torsvik and Cocks, 2017; Vérard, 2019). Therefore, the observed differences between GPMs are not due simply to declining data availability with increasing age, but also to the use of that data and expert implementation (see Textbox 1). However, in times with low data availability and low data confidence (such as the palaeomagnetic data in the Devonian) variation between models can reduce (see Buffan et al., 2023), indicating consensus under constraint rather than increasing accuracy (see van der Boon and Dowding, this volume).

One key example is the treatment of Large Low Shear Velocity Provinces which sit at the core-mantle boundary (LLSVPs; see the review by Gülcher et al., 2021). The work of Torsvik et al., (2014) makes a functional assumption that LLSVPs are relatively static and have maintained their antipodal and equatorial position for over 300 million years. At their edges, the lowermost mantle flow is driven into the denser LLSVPs and deflected upward leading to Plume Generation zones, and mantle plumes above which Large Igneous Provinces are hypothesised to erupt (LIPs; Torsvik et al., 2025; Torsvik and Cocks, 2017). Under the assumption that LLSVPs are relatively stable, then it follows that Plume Generation zones are also stable and their presence can be used as an additional longitudinal constraint on past plate positions (Torsvik et al., 2008; Torsvik et al., 2014; and Torsvik et al., this volume). However, the reliability of this approach depends on the assumption of stability, an idea that is not universally accepted (see Gülcher et al., 2021; Müller et al., 2022; Seton et al., 2023; Torsvik et al., 2014; Torsvik and Cocks, 2017; Vérard, 2019 for discussion). These differences can lead to substantial longitudinal divergence in model outputs, especially for time periods preceding the assembly of Pangea (see Torsvik et al., 2008; 2014; Müller et al., 2022).

Further, the changing availability and quality of data has led GPM developers to rely on different, and often less easily integrated datasets, such as fossil biogeographic information (van der Boon et al., 2022; Seton et al., 2023; Dowding et al., this volume). For example, data from fossils and facies are included to various degrees within different approaches. Among the three models this piece uses, the `MERDITH2021` model does not include any novel fossil data directly, though they are inherited from earlier models (e.g. Domeier, 2016; 2018), whilst `PALEOMAP` (Scotese and Wright, 2018) incorporate reef occurrences (a climatically and latitudinally sensitive facies) as secondary checks to reconstructed plate position, whilst `TorsvikCocks17` uses reef occurrence and organism co-occurrences to latitudinally constrain and inform relative positioning. These data and implementation differences between models can propagate into palaeobiological conclusions (Torsvik et al., 2025). These procedural and data inclusion choices can significantly shape the resulting palaeogeography and downstream palaeontological analyses, highlighting the need for transparency in model construction,

inventorying the ingested data, and critical engagement with the assumptions underpinning tectonic reconstructions.

2.4. Model structure

GPMs consist of two main components:

- **Geometries:** spatial divisions of Earth's surface into tectonic elements represented visually for users.
- **Reconstruction trees:** hierarchical frameworks linking plate motions through finite rotations allowing calculation of plate positions within a reference frame.

Geometries divide Earth's surface into tectonic elements, represented as polygons, that can be reconstructed independently, with some being dynamic (changing through time) and others being fixed (static). For example, static polygons act as rigid, unchanging shapes that define plate IDs for the partitioning of other data (such as fossil localities), while the reconstructed positions of the modern coastlines provide a visual aid for navigating palaeogeographies with those plates (see Textbox 1). Different interpretations of tectonic boundaries, especially in complex geological regions and older time periods, can lead to substantial differences in how the Earth's surface is divided and represented in various models (see Textbox 1).

Reconstruction trees (or rotation hierarchies) organise relative plate motions (rotations) to determine the absolute motion of any plate relative to a fixed, anchored plate. Plates are linked through a series of parent–child relationships in a structure that ensures internally consistent plate motions and enables efficient calculation of palaeogeographic coordinates.

Most users will use only the output of a given GPM. For further details see the relevant model documentation, software user guides (e.g. *GPlates*; Scotese, 2016; Chin, 2023), or expert reviews (e.g. Svensen et al., 2018; Domeier et al., 2023; Seton et al., 2023).

3. GPM Resources

3.1. Tectonic modelling software and model data

The tools dedicated to working with GPMs have expanded in number, making tectonic reconstructions increasingly accessible to users. The most widely used software is *GPlates*, a GIS desktop application that provides a graphical interface for visualising and manipulating plate reconstructions (Müller et al., 2018). Together with the *GPlates Web Service (GWS)*, an online web application to execute reconstructions, it forms the basis of an open suite that allows users to access GPMs and derived products such as palaeogeographies.

The underlying functionality of *GPlates* is exposed programmatically through *pyGPlates*, a Python package that enables direct interaction with model geometries, rotations, and reconstruction trees (Gurnis et al., 2018; Mather et al., 2024). While *pyGPlates* allows

interaction at a lower level of abstraction, enabling more detailed and flexible analyses, it comes with increased computational and technical complexity.

To facilitate easier use, several dedicated higher-level programming packages have been developed. These include *gplately* (Python; Mather et al., 2024), *gwspy* (Python; Chin, 2023), and *rgplates* (R; Kocsis et al., 2024), which provide user-friendly programing interfaces for common reconstruction tasks without requiring full access to GPM backend. The *GWS* further reduces computational barriers by enabling remote execution of standard reconstruction operations via HTTP requests (Chin, 2023). The *GWS* services are integrated into multiple pipelines (*rgplates, gwspy* and, *palaeoverse* (Jones et al., 2023) and can be accessed through public instances, deployed locally or on remote servers. In some cases, users may bypass direct interaction with GPMs entirely by employing pre-computed palaeocoordinates (e.g. Jones and Domeier, 2024), which can simplify analyses where only reconstructed positions are required—at the cost of discretising space and time.

3.2. Palaeogeographic data products derived from GPMs

Palaeogeographic reconstructions extend GPMs by incorporating geological and environmental information to model past Earth-surface conditions. Palaeogeographies integrate topography, bathymetry, flooding extent, exposed land area, depositional environments, and derived Digital Elevation Models (DEMs), usually made available in combinations (e.g. Cao et al., 2019; Scotese et al., 2025; Torsvik and Cocks, 2017). Such reconstructions are not independent datasets: they are derived from, and therefore contingent upon, a specific GPM. For example, the widely used palaeo-DEMs of the PALEOMAP project inherit their plate configurations directly from the underlying plate model (Scotese et al., 2025)—even if the reconstructed landmass distribution deviates from the plate model locally.

GPMs define the absolute position, orientation, and relative configuration of continents and ocean basins through time; palaeogeographic reconstructions inherit these plate geometries and elaborate them using geological context, such as continental margins, orogenic belts, and environmental indicators preserved in the rock record (e.g. redbeds, evaporites, coals, tillites, and reefs to infer geography and environment (Boucot, 2015; Boucot et al., 2013; Cao et al., 2019; Marcilly et al., 2022; Scotese et al., 2025). These proxies are used to infer climatic zones, depositional settings, and environmental gradients across deep time (e.g. Scotese et al., 2021).

Most global palaeogeographies are constructed at discrete temporal intervals, typically every 1–5 Myr (and up to 10 Myr), with the possibility of interpolation between time slices. As a result, they represent long-term average conditions rather than short-term variability. This temporal smoothing can produce mismatches between reconstructed environments and fossil occurrences; for example, marine taxa plotted on nominally terrestrial surfaces. Local and regional landscape evolution can be more precisely mapped using field geology techniques or landscape evolution (such as *BADLANDS*, Salles, 2016; and *goSPL*, Salles et al., 2020) and carbonate stratigraphic models (e.g. *CarboKitten.jl*, Hidding et al., 2025).

Secondary Earth System Models, including general circulation models and climate models, are in turn derived from the reconstructed palaeogeographies (Marcilly et al., 2025; Valdes et al.,

2021; Fig. 2). Climate reconstructions typically focus on specific intervals of time, or applications of specific test-cases, which are used either to study the history of geochemical cycling (e.g. *SCION*, Mills et al., 2025) or by palaeontologists to assess influence on long-term changes of the biosphere (Kocsis et al., 2018a; Ontiveros et al., 2023) or crisis intervals (Penn et al., 2018; Saupe et al., 2020; Landwehrs et al., 2021; Reddin et al., 2025). Examples of Phanerozoic-scale climate reconstructions are available to the general public using the `PALEOMAP` model include *cGENIE* (Pohl et al., 2022), *HADCM3* (Valdes et al., 2021) and *CLIMBER-3α* (Li et al., 2022).

Together, GPMs, palaeogeographies, and other ESMs form an internally consistent but hierarchically dependent framework for reconstructing Earth's physical and ecological conditions. Consequently, palaeontological interpretations of climate, habitat availability, and biotic distributions are conditional on the lineage of the global plate model and its derived products (e.g. Fig 1). Statistical uncertainty can then only be considered within an individual modelling lineage and framework, rather than between them. Best practice therefore involves careful assessment of model provenance, resolution, and compatibility with the research question.

4. Suggestions and recommendations

Effective use of GPMs in palaeontology begins with clearly defining analytical requirements. Most applications rely on either:

1. Attributes of a time interval (e.g. average temperature, continental flooding), which may not require the use of a GPM directly; or
2. Location-specific variables (e.g. palaeocoordinates of occurrence records, their implied spatial relationships and environmental context), which require integration of GPMs and derived ESM outputs into analytical workflows.

In many cases, reconstructed palaeocoordinates are used to derive broader environmental variables that serve as covariates in evolutionary analyses. Within this subset, model selection should be guided by the specific requirements of the analysis rather than by the full theoretical scope of the GPM. Many palaeobiological studies do not require complete geodynamic histories or detailed plate boundary reconstructions, but instead depend on robust, internally consistent palaeocoordinates at relevant spatial and temporal scales.

Consequently, the recommended workflow should focus on appropriately extracting information from specific models (whether GPM or ESMs) needed for the biological question at hand, and ensure the results are robust to GPM selection. Although many of the following recommendations might be straightforward for experienced users, they hope to serve as a transparent, and reproducible approach for selecting, interrogating, and applying GPM-derived data products to palaeontological analyses. These recommendations assist users in assessing if model choice and implementation remain aligned with the scientific question being addressed.

4.1. Define research scope and data requirements

When designing a study that integrates fossil data with GPMs, the first step is to clearly define the scope of the research and determine whether GPM integration is necessary at all (Table 1). Not all analyses require recalculation of past plate positions or coordinate-level reconstructions; many can rely on pre-calculated data and previously published palaeogeographic maps. Avoiding unnecessary computations and using only the data required to meet the study's objectives improves efficiency, transparency, and reproducibility. In practice, the direct use of dynamic GPM reconstructions can often be replaced by: (1) previously calculated numerical variables, and (2) published palaeogeographic snapshots (static reconstructions).

Spatial scope. GPMs are generally recommended for global and continental level analyses. At these scales, users may require a summary of large-scale characteristics of continental configuration, climate state, and tectonic–environmental interactions, such as continent fragmentation, flooded continental area, or mean global air temperature (e.g. Kocsis and Scotese 2021; Marcilly et al., 2022). While these metrics remain dependent on underlying GPMs, they are generally less sensitive to coordinate-level uncertainties and are therefore easier to integrate critically; see Antell et al., (2024) and Close et al., (2018) for a summary of best practices.

Regional or local studies, by contrast, may not require full GPM integration. Where spatial focus is limited (e.g. a basin, terrane, or continent), previously published static reconstructions or GIS-based palaeogeographies may provide higher fidelity representations of geological context. Tools such as *TerraAntiqua* (Aminov et al., 2023), which integrates *QGIS* (Dawson et al., 2025) and *GPlates* (Müller et al., 2018), allow interactive construction and modification of palaeo-DEMs. In such cases, smaller spatial scope permits more precise representation of sedimentary environments and land–sea distributions, which are often averaged in global models (Cao et al., 2017, 2019). For simple contextualisation, such as visualising fossil localities, static reconstructions combined with regional geological literature may suffice (e.g. Holmer et al., this volume).

Temporal scope. Analyses focusing on single localities or regions that have limited scope in geological time are likely to benefit more from in-situ palaeoenvironmental reconstruction rather than by integration with a GPM or derived data products. However, research spanning longer timescales generally requires broader spatial integration and thus benefits from tectonic contextualisation. Temporal binning, commonly using intervals of the Geological Time Scale (GTS), aligns estimated fossil ages with reconstruction targets (see 'target age selection' and 'terrane duration' Section 4.3.). Whether using original data or those stored in open access repositories such as the Paleobiology Database (*PBDB*), resolving regional chronostratigraphic frameworks to the GTS in databases is discussed by Wang et al. (2025) and best practices for standardising is discussed by (Flantua et al., 2023). The mixed use of regional and global timescales in community databases, such as the PBDB, can cause further complications and can be harmonised using software packages such as *fossilbrush* (Flannery-Sutherland et al., 2022). In cases, however, when the history and dynamics are debated or variable, e.g. the Tasmanides of Eastern Australia, the user interpretations of reconstruction should be informed by geological context (Textbox 1).

Computational needs. Analyses addressing dispersal pathways, range shifts, spatial turnover, or bioregionalisation typically require explicit reconstruction of palaeocoordinates. Static reconstructions are often unsuitable for quantitative spatial analysis but results of GPMs can be integrated into computational workflows.

Characterisation of localities. GPMs and derived products (e.g. general circulation and geochemical models) enable geographic and environmental contextualisation of fossil localities. When reconstructed positions inform numerical variables or are used in downstream analyses, tectonic reconstruction is required. Locality-level proxy data may also contribute to the derivation of global-scale variables, reinforcing the need for consistent spatial frameworks.

4.2. Palaeogeographic data and model selection

If GPM use is justified, analyses must be grounded in a clearly defined set of models, derived products (ESMs), and methods. The suitability of a GPM depends on its temporal coverage, spatial resolution, available derived products, and accessibility. Not all models are appropriate for all research questions, making careful evaluation essential.

In practice, most palaeontological studies rely on a single primary GPM (occasionally two), which underpins the analytical pipeline and provides a coherent palaeogeographic framework for calculations and visualisation. Where possible, additional models should be used to assess sensitivity, with the responsibility resting on the user to evaluate how results depend on model choice.

Reference frame. The reference frame is a critical attribute. For palaeontological applications, especially in the Palaeozoic, palaeomagnetic reference frames are required (Leonard et al., 2025; Torsvik et al., 2012). Although discrepancies between palaeomagnetic and mantle reference frames decrease toward the present, differences can remain significant enough to impact interpretations.

Temporal scope. The temporal range of a GPM must match the research question. This is particularly important for pre-Mesozoic studies, as not all models extend through the Palaeozoic (e.g. Domeier and Torsvik 2014; Merdith et al., 2017; Alfonso et al., 2025). Similarly, derived products such as climate simulations are often restricted to specific intervals and should be used with their parent GPM (e.g. Valdes et al., 2021 with `PALEOMAP`).

Spatial focus. Model suitability may vary by region. While GPMs share common foundations, many include regionally refined datasets, resulting in higher resolution (e.g. increased terrane detail or event chronology) in certain areas. Selecting a model with appropriate regional fidelity can improve the spatio-temporal resolution of analyses (e.g. Textbox 1).

Secondary data products. Availability of derived datasets, such as palaeogeographies, climate simulations, oceanographic reconstructions, can strongly influence GPM choice. Lack of available reconstructions of an Earth System variable does limit the choice of GPMs that are applicable in an analysis.

Model assumptions. Ideally, the data and the development process of GPMs and derived models should be made available by their developers and also should be explicitly considered by users. The inability to do so risks circular reasoning, particularly where fossil or environmental data are already incorporated into model development. Researchers should assess which data are included into GPMs and ESMs and how they influence both the reconstructions and the interpretation of palaeobiological outputs (e.g. reefs distributions, Dowding et al., this volume).

These previous phases of developing an analytical pipeline (i.e. Steps 1 and 2 in Table 1) are often iterative: refining research questions may require revisiting model selection, and vice versa. If no suitable combination of models and data exists, this may indicate that required datasets have not yet been developed, highlighting opportunities for collaboration with palaeogeographers.

4.3. Implementing calculations with GPMs

Implementation begins with a clear understanding of how reconstruction outputs will be used within the analytical pipeline. Software choice depends on the complexity of GPM manipulation, required quantitative methods, and researcher expertise (Table 1).

Reproducibility. Reproducibility is a high priority of good scientific practice. Keeping workflows simple and implementing analyses within programming environments enhances transparency and repeatability. While software with a graphical interface (e.g. *GPlates*) may suffice for single time slices or small datasets, multi-temporal analyses are more efficiently handled programmatically.

Programming environments. Python and R are the primary environments for GPM-based analyses. For dedicated packages, Python supports tools such as *pyGPlates*, *gplately*, and *gwspy*, while R users may prefer *rgplates*. Maintaining analyses within a single environment improves reproducibility, though outputs can be exported to standard GIS formats for further processing. If model modification is required, direct use of *GPlates* or *pyGPlates* is typically necessary. Local execution of calculations is generally preferable to remote services (e.g. *GWS*), as it ensures access to data and code for documentation and reuse. Remote services may still be appropriate when they can be hosted locally.

Target age selection. Fossil data are rarely synchronous, requiring temporal discretisation. Target ages should align with estimated ages of localities or with predefined temporal bins (e.g. midpoint of GTS intervals). Consistency is essential: reconstructions and associated datasets that are used together to describe the same interval of time must use the same target age and GPM. When integrating secondary products (e.g. DEMs or climate outputs), locality reconstructions must match the temporal framework used to generate those products.

Terrane durations. GPM polygons have defined temporal ranges ('using '*from*'—'*to*', given as ages in Ma). If an occurrence datum's age (*t*arget age) falls outside these bounds, reconstruction may fail or produce invalid coordinates (e.g. *pyGPlates* will return modern coordinates and *rgplates* returns 'N/A') values. Both *GPlates* and the *GWS* (and resources using

them) allow reconstruction beyond valid durations (set with the 'validtime' argument), but this introduces inconsistencies and should be limited (typically ≤1–5 Myr) and treated with caution. The extent of such mismatches should be quantified, and sensitivity analyses conducted to assess their impact.

Workflow organisation. For computational efficiency and to prevent unnecessary re-calculations of tectonic reconstructions, GPM use is recommended to be separated from downstream analyses. For the sake of reproducibility, all steps, as well as software versions and data sources, need to be documented and computer code to be archived (e.g. Dowding and Kocsis, 2026).

4.4. Integration with analytical workflows and sensitivity assessment

Reconstruction outputs can be integrated into broader analytical pipelines. Integration requirements determine subsequent tools and languages, with R being used most commonly by palaeontologists for statistical, ecological, and biodiversity analyses. A guiding principle is to use the simplest and least derived data product capable of addressing the research question. Minimising reliance on highly derived datasets reduces propagation of artefacts that can be misidentified as variance or important palaeobiological signals. Although results are often presented using a single primary GPM, analyses are best repeated with alternative models where possible to assess robustness.

Comparative evaluation across models is essential. The effects of GPM choice is expected to propagate through the analytical pipeline creating variance in statistics as well as in visual products. This variance must be assessed from the central hypotheses' perspective. Researchers should assess whether inferred patterns, such as species ranges, dispersal pathways, or biogeographic barriers, are robust to differences in tectonic and palaeogeographic reconstructions. Sensitivity analyses help distinguish genuine biological signals from artefacts of model construction and clarify which aspects of palaeogeography drive observed results. Additional calculations and elaborate discussion might be indicated if GPM choice affects decisive results.

5. Community contributions

Establishing more efficient communication between the communities of GPM developers and users will serve to improve outcomes of both in the near future. GPM users can better exploit the scientific opportunities offered by GPMs, and developers can better integrate biological and facies data into tectonic models, improving the consistency of Earth–life reconstructions. Establishing shared standards for documentation, data accessibility, and model evaluation is critical for advancing the field.

Adopting best-practice data principles such as FAIR (Findable, Accessible, Interoperable, Reusable) and CARE (Collective Benefit, Authority to Control, Responsibility, Ethics) offers a major opportunity to strengthen collaboration between GPM developers and users (Wilkinson et al., 2016; Carroll et al., 2020; Jacobsen et al., 2020; Murphy et al., 2020). Palaeontologists can contribute valuable expertise on fossils, environments, and lithology, improving both palaeogeographic reconstructions and derived products such as climate models (Wong-Hearing et al., 2021; Dowding et al., this volume). When shared openly, such contributions become reusable resources that benefit the broader community. For users, clearly reporting the GPM's name, version, reference frame, and datasets employed improves reproducibility and comparability. For developers, open archiving facilitates uptake, critique, and iterative refinement. Together, these practices create a feedback loop in which models are tested, improved, and increasingly integrated into Earth–life science research.

6. Conclusion

Global plate models provide internally consistent reconstructions of Earth, integrating kinematics, palaeomagnetism, geological constraints, and geodynamic principles into coherent frameworks. From these foundations flow a rich suite of derived data products, palaeogeographies, digital elevation models, flooding maps, climate simulations, ocean circulation models, and related nutrient cycles, that together allow Earth system processes to be explored in ways that were inconceivable only a few decades ago (see Fortey and Cocks 2003; Cocks and Fortey, 1982). These tools have transformed how we investigate long-term climate evolution, biodiversity patterns, biogeochemical cycles, and resource formation, and they increasingly serve as a common language linking solid Earth, climate, and life sciences.

GPMs remain evolving hypotheses rather than definitive reconstructions. Both the models themselves and their applications remain actively under development. The history of the field makes clear how transformative methodological innovation can be: the hand-drawn maps of A. Wegener laid conceptual foundations that ultimately enabled today's fully dynamic, quantitatively constrained plate and climate reconstructions. Today’s GPMs represent a similar inflection point rather than an endpoint. As data coverage improves, computational methods advance, and closer collaboration develops between modellers and data-rich communities such as that of palaeontologists, the scope of Earth system science will continue to expand. By embracing openness, interoperability, and cross-disciplinary engagement, the community is well positioned to develop the next generation of models, capable not only of reconstructing past possible Earths, but of revealing new, integrative insights into the coupled evolution of the planet and its biosphere.

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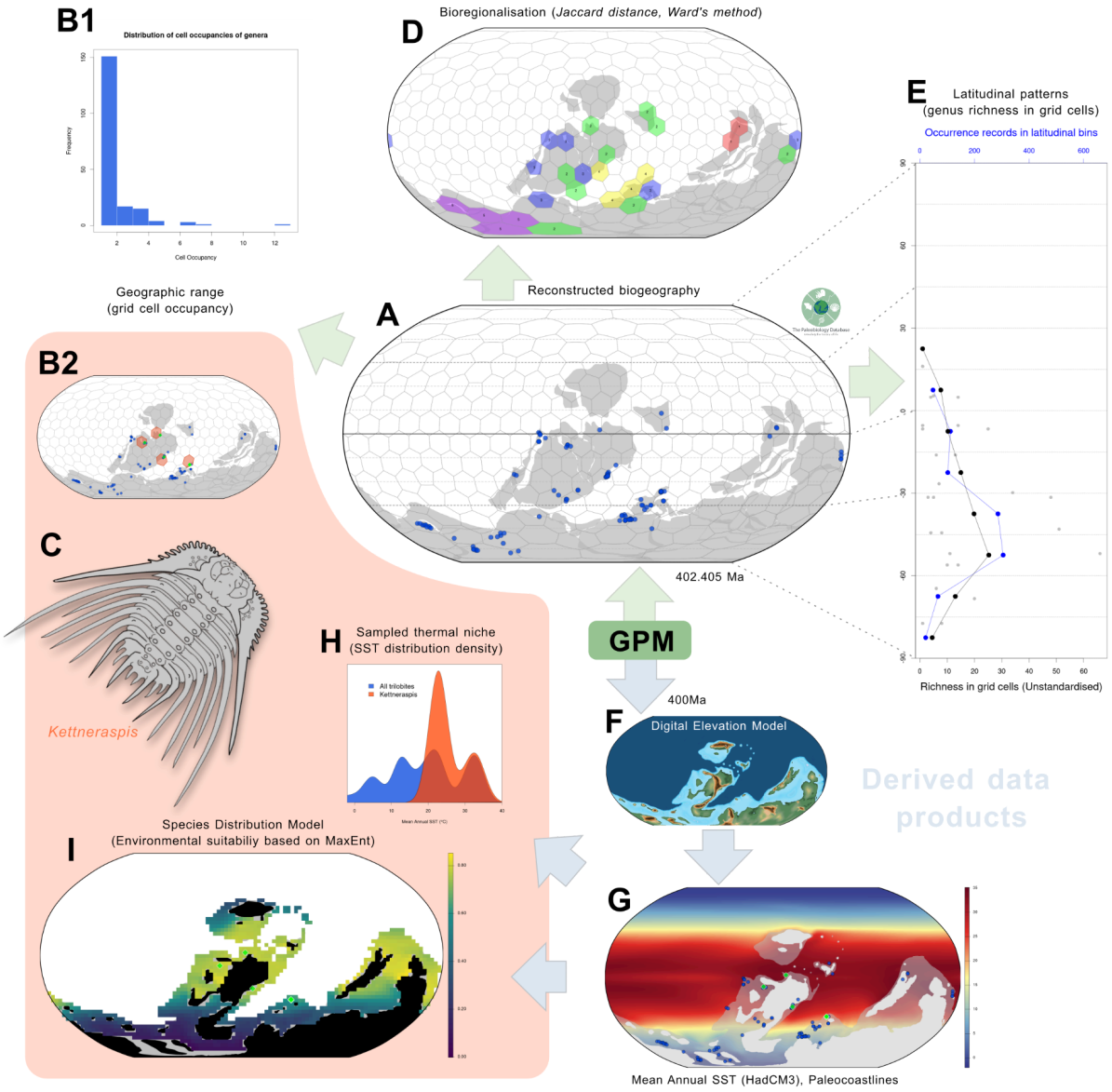
Data availability

The produced computer code and used data are made available on Zenodo (Dowding and Kocsis, 2026).

Figures



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551 **Figure 1.** Example potential use cases of GPMs and palaeogeographic data products in
552 palaeobiology, illustrated with preliminary analyses of Emsian (Early Devonian) trilobites fossil
553 data from the *Paleobiology Database* (February 2026) and the `PALEOMAP` GPM and
554 palaeogeographic data products. Arrows indicate the flow of information and reverse
555 dependency. A. Reconstructed plate polygons can be used to visualize fossil distributions using
556 the reconstructed paleocoordinates of their localities. Reconstructed localities can be used to
557 calculate geographic ranges (B1 for all genera, B2 for the example genus *Kettneraspis,*
558 illustrated in panel C), demonstrated here with grid cell occupancies. Palaeocoordinates form
559 the basis of bioregionalization studies in reconstructed space (D), and the assessment of

latitudinal diversity gradients of diversity and spatial patterns of sampling (E). Calculations using derived data products (e.g. those based on PALEOMAP DEMs, F) need to use their inherent target age for a consistent reconstruction. Examples include results of climate models (e.g. G, that can also be used to contextualise fossil data), inferring about the ecological niche (H), or using it in habitat suitability or distribution modelling (I). The examples shown here are illustrations of general analytical pipelines. See deposited code (Dowding and Kocsis, 2026) for details.

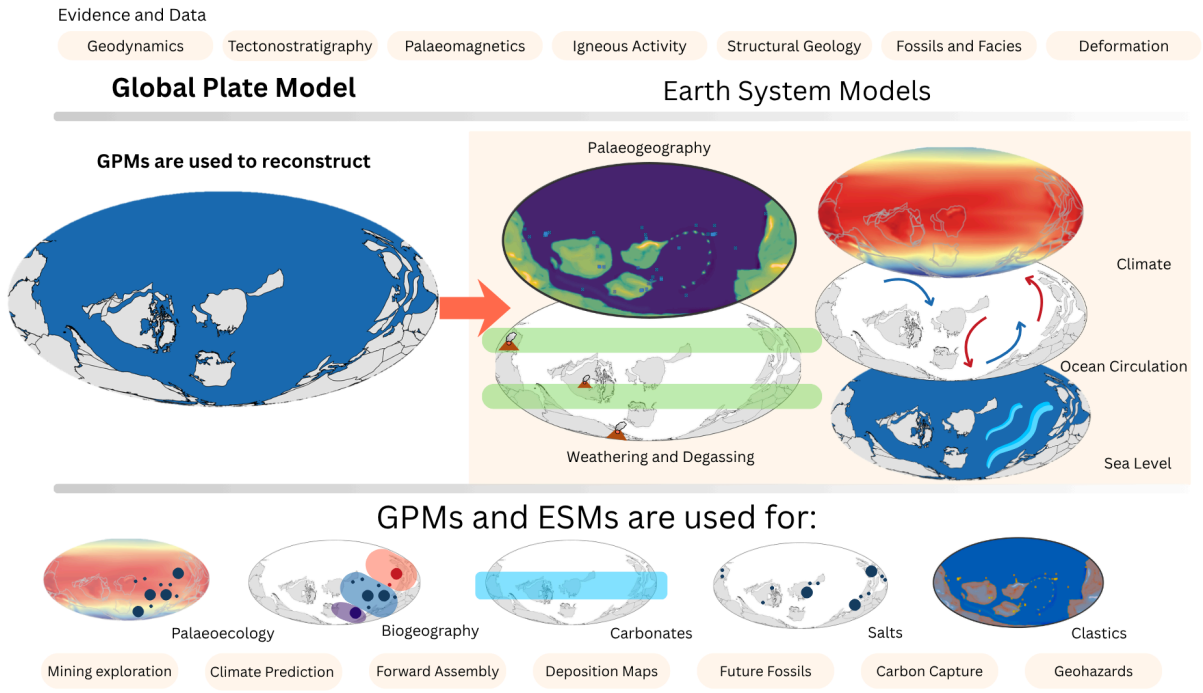


Figure 2: The relationships between global plate models (GPMs) and their derived data products, including palaeogeography and palaeoclimate. GPMs form the foundation for multi-level Earth system reconstructions, allowing the analysis of climatic, sea level, and biological evolution through time. The GPMs and their stacked data products create internally consistent Earth System Models (ESMs). They offer dynamically reconstructed hypotheses of the tectonic development of Earth, with the evidence provided from the modern world rotated back through time to a target age, here 500 Ma, the Cambrian, using the PALEOMAP tectonic model and the climate model derived from it (Valdes et al., 2021).

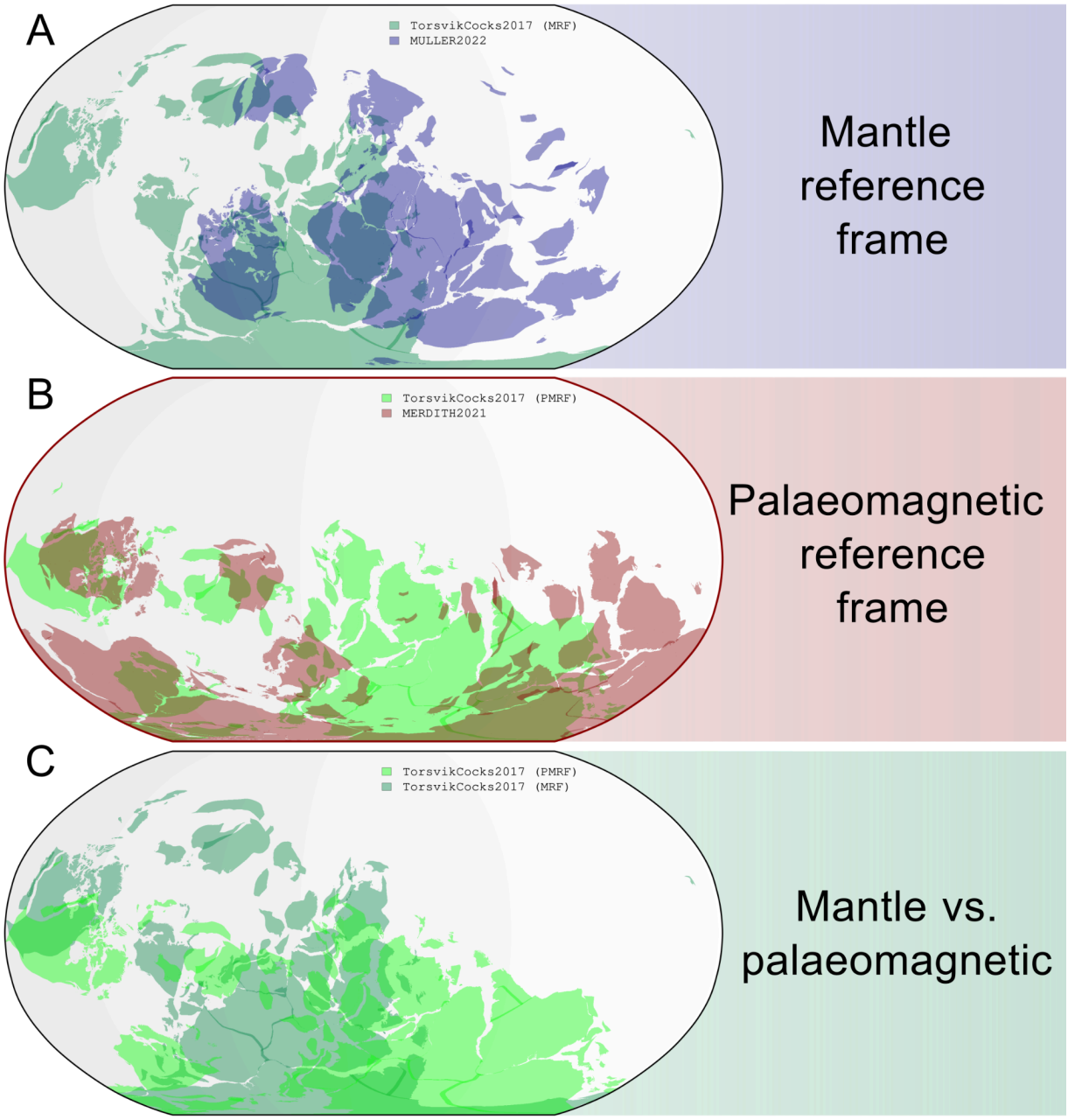


Figure 3: Comparison of reconstructions (modern landmasses partitioned to plate polygons, 'coastlines' feature collection) within the same (A: mantle reference frame, B: palaeomagnetic) and between different reference frames (C, using the same GPM, `TorsvikCocks2017`). The target age for the reconstruction is 500 Ma (Cambrian). Note the major differences in reconstructed latitudes when the same relative motions are used with a different reference frame (C). More saturated areas in a single reconstruction indicate necessary overlaps of the non-deforming plate polygons.

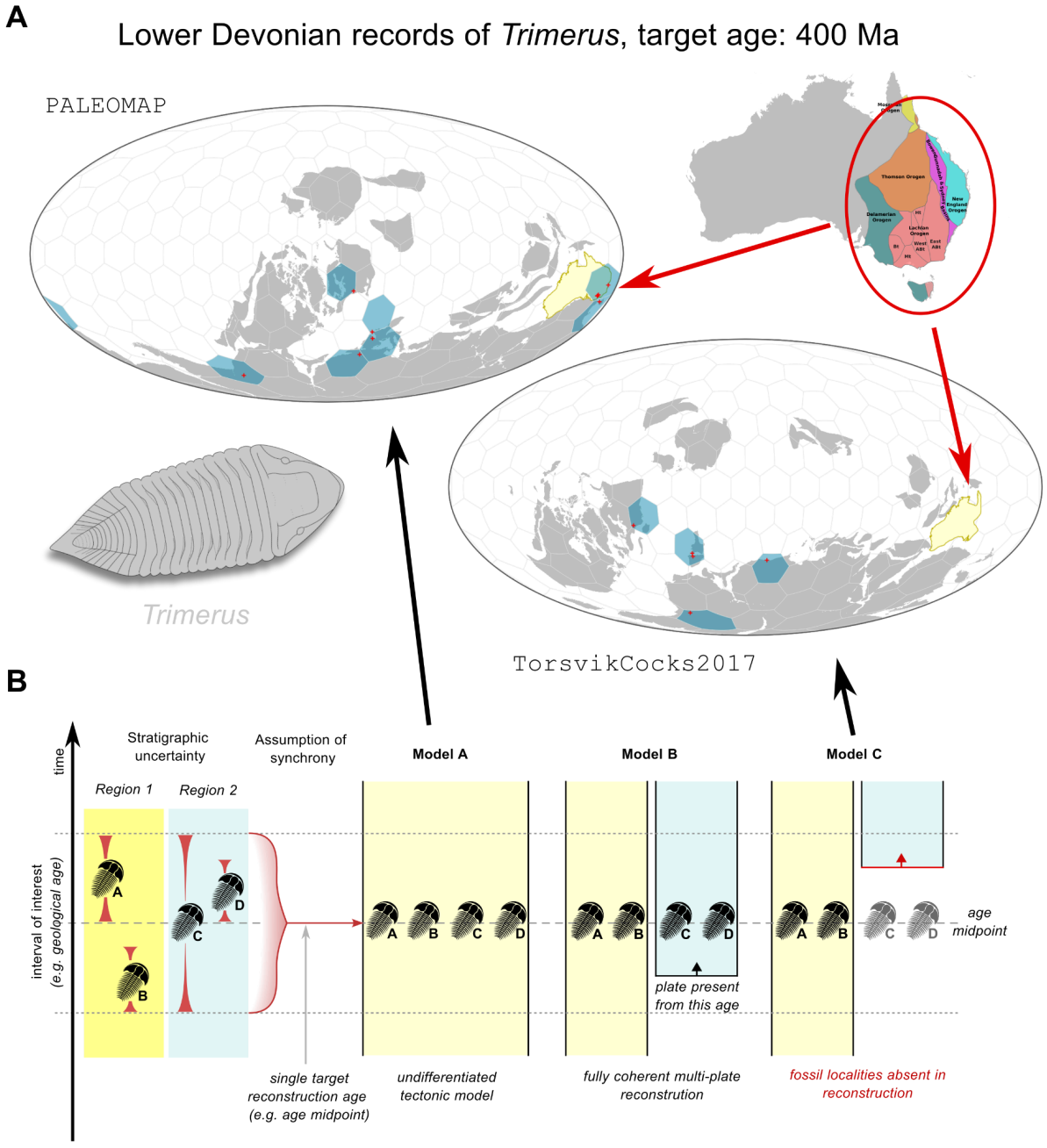
Tables

Step	Checkpoints to review
1. Define research scope and data requirements	a. Spatial scope. (global, regional, local) b. Temporal scope. (Phanerozoic, Emsian) c. Required Earth System variables. (temperature, shelf area) d. Type of reconstruction required (dynamic, static)
2. Palaeogeographic data and model selection	a. Temporal and spatial scope matches research b. Appropriate GPM reference frame is used c. Tally available secondary data products, ensure their attributes match research requirements d. Review assumptions of GPMs and secondary data e. Select primary GPM and those used in sensitivity testing
3. Implementing calculations with GPMs	a. Plan the use of GPM-based results b. Select software implementation c. Review target ages for data reconstruction; prototype pipeline with primary GPM d. Assess whether plate duration/target age mismatches affect reconstructions e. Store results of GPM calculations for efficient reuse f. Assess reproducibility, document used data and software packages.
4. Integration with analytical toolchain and sensitivity assessment	a. Recalculate main results with additional GPMs b. Assess sensitivity of hypotheses to GPM choice and interpret discrepancy in face of GPM characteristics

Table 1. A summary of recommended steps for integrating GPM-based calculations into palaeontological analyses.

Text boxes

Textbox 1: Spatiotemporal mismatch and the effects of plate partitioning and duration on palaeontological reconstructions.



Box-Figure 1. (A) Distribution of *Trimerus* plotted on two plate reconstructions, illustrating differences between geological history of Australia (particularly the Tasmanides) and static polygon representations in PALEOMAP and TorsvikCocks17. Fossil occurrences of *Trimerus* are retained in PALEOMAP despite geological inaccuracy, but are excluded in TorsvikCocks17 due to Australian plate partitioning and the absence of valid 'from'–'to' ages at 400 Ma. (B) Schematic showing how plate temporal duration ('from'–'to') controls whether geographic positions of fossil occurrence records can be reconstructed.

GPMs represent the reconstructed plates with non-deforming geometries, such as '*static polygons'* or '*coastlines'*. In both cases, these representations are derived from modern geological evidence, which preserves only the present-day expression of lithological units (e.g. cratons) or the coastlines of today. Currently, tectonic models cannot account for deformation through compression (e.g. folding during orogenesis) or extension (e.g. rifting and lithospheric stretching), the past extent of a continent may have been substantially larger, smaller, or differently shaped than its modern expression. As a consequence, the true spatial extent and shape of lithological units in deep time are not directly represented in GPMs, only the reconstructed positions.

Australia provides a clear example of how these representational choices propagate into palaeontological analyses. The Australian continent comprises at least four major tectonic elements, three cratons forming the western portion, and the Tasmanides accretionary complex in the east. During the Devonian (~400 Ma), the Tasmanides, composed of more than ten fossiliferous tectonostratigraphic terranes and four major orogens, had not yet accreted to cratonic Australia and did not form a single unified continental block (Dowding and Ebach, 2016; Rosenbaum, 2018). However, tectonic plate models differ markedly in how this configuration is represented: some use the full modern Australian coastline (e.g. `PALEOMAP`), others reconstruct only the western craton and omit the Tasmanides (`TorsvikCocks17`), represent them as a single accreting block (Torsvik et al., 2025) or as oceanic crust (`MERDITH2021`).

As a result, palaeontological analyses that rely on reconstructed distances, areas, or connectivity inherit the assumptions embedded in plate partitioning and their representation as static polygons and coastlines. These differences can strongly influence inferred range size, occupancy, and biogeographic structure, independent of biological signal, underscoring the need for explicit model choice and lineage-aware interpretation.

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