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Deconstructing plate tectonic reconstructions

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Key Points

- Plate tectonic reconstructions have evolved from simple, rigid reconstructions to ones that incorporate the time-dependent evolution of plate and their boundaries, deformation and/or the history of subduction from seismic tomography
- Reconstructions can be powerfully predictive for a wide range of disciplines beyond tectonics, including palaeobiology, palaeoclimate, geodynamics, and seismologyThere is no 'one-size-fits-all' when it comes to reconstructing the Earth's tectonic plates: different data types and techniques are applicable for different time periods, resolutions and purposes.
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- Important areas of ongoing research include the quantification of uncertainty, linking reconstructions to physics-based deep-Earth to surface (and biogeochemical) models and the incorporation of machine learning techniques

Abstract

The evolving mosaic of continents and oceans sets the boundary conditions for biotic and abiotic processes across the Earth's surface, and helps shape the dynamics of its interior. Reconstructing plate tectonics back through time with open-source plate reconstruction software, like *GPlates*, allows scientists from a range of disciplines to consider their data through these evolving spatio-temporal dimensions. Methodological innovations, such as the modelling of entire plates with continuously evolving boundaries, accounting for plate deformation, and the incorporation of information from seismic tomography, are moreover opening new research frontiers in fields such as palaeobiology, palaeoclimate, geodynamics and seismology. However, there is no 'one-size-fits-all' and users need to choose the right model for a given purpose to avoid circular reasoning. In this Technical Review, we provide an accessible manual of the construction process behind quantitative plate reconstructions, and highlight their limitations and some common pitfalls faced by their users. Future work on intercomparisons between models and uncertainty quantification are an essential pathway towards next generation plate reconstructions.

Introduction

Plate tectonics–the surface expression of Earth's interior dynamics–incessantly reshapes our planet's geography, and has played an integral role in the history of climate and the biosphere. The changing distribution of the continents through supercontinent cycles of dispersal and amalgamation has, amongst other things, influenced ocean and atmospheric circulation patterns and chemistry; controlled major sea-level fluctuations; driven surface weathering, erosion and sedimentation; and regulated the migration and evolution of biota. An understanding of palaeogeography and plate tectonics is thus vital to a wide variety of scientific endeavours.

The principles of plate tectonics were first formulated and applied to making quantitative plate reconstructions in the 1960s[1–4], and in the subsequent decades there followed a steady development of new reconstruction models and approaches[5–10] and an attendant growth in their application. Many early approaches were schematic representations of continental movement at discrete snapshots in time. Others incorporated the history of seafloor spreading and/or the representation of plate boundary networks. However, for much of the last half-century, the construction and application of plate tectonic reconstructions were largely confined to the domain of specialists, even with the advent of dedicated software tools[11–13]. This changed with the introduction of open-source, geographic information system (GIS)-type user-oriented plate reconstruction software, such as *GPlates*[14,15], in the early 2010s, which instigated an explosive growth in the generation and application of plate reconstructions by the wider Earth science community. No longer passive end-users, non-specialists have been handed the tools via an user-friendly interface to develop reconstructions based on their own domain-specific datasets and expertise.

Modern, multifaceted plate reconstructions provide the universal language to connect once disparate individual Earth-science domains and data into a common framework and have been instrumental in unlocking the vast potential of an integrated geological record. Such integration has advanced our understanding of the internal dynamics of our planet[16–22], Earth's long-term biogeochemical cycles[23,24] and biodiversity through time[25–27]. The accessibility of these models has also facilitated advances in applied areas, for example linking mineral systems and their prospectivity to tectonic parameters[28–30] and unraveling tectonic controls on natural hazards[31,32], and they have likewise promoted education and outreach[33,34]. However, as these models have entered the domain of non-specialists, it is timely to unpack the current state-of-play in terms of the development, use and future direction of plate tectonic reconstructions.

In this Technical Review, we discuss the key data that underlie global plate tectonic reconstructions, the various flavours of reconstructions generated from these data, and provide some tangible examples of how these reconstructions have been applied to address big picture questions in the Earth sciences. Lastly, we convey a set of principles on how to generate and use (but not abuse) plate tectonic reconstructions. We emphasise the need to understand and consider the limitations and uncertainties inherent in any reconstruction.

Key data sources

Since the time of Alfred Wegener[35], reconstructions of paleogeography have been underpinned by a synthesis of data from a variety of sources and tectonic environments (FIG. 1). Over time, and with new conceptual understandings of how our planet works, from continental drift to plate tectonics, the geoscientific community has built a structured hierarchical system of relative and absolute plate motions to describe the motions of plates through time (BOX 1). New techniques for interrogating the geological record and understanding geodynamic principles have continued to emerge across the past century, providing increasingly more constraints that can be fed into plate tectonic models. In the following, we succinctly review the key data/constraints, starting with palaeomagnetics that first quantified continental drift to more recent geodynamic interpretations.

Palaeomagnetics

On timescales of 10^5-10^6 years, the Earth's magnetic field can be approximated by a geocentric axial dipole (GAD) [G], where the vertical component of the field is related uniquely to latitude and the horizontal component is everywhere directed north (or south when the field polarity is reversed). Rocks can acquire a magnetization when they form, and are thereby imprinted with a quantifiable record of their original palaeolatitude and azimuthal orientation. However, owing to the axial symmetry of the magnetic field, individual palaeomagnetic records do not constrain longitude. Reconstructions based on palaeomagnetic records can be continued backward in time as far back as primary magnetizations can be recovered, and so long as the GAD hypothesis holds (widely assumed valid at least back to the early Proterozoic[36,37]). Accordingly, the palaeomagnetic records from some continents span billions of years, whereas apart from sparse data from ophiolites, palaeomagnetic records from the oceanic lithosphere (where far fewer samples exist) are restricted to the last ~180 Ma.

Increasing volumes of palaeomagnetic data are now being publicly archived in the community-driven Magnetics Information Consortium (MagIC: https://www2.earthref.org/MagIC) database and the Global Paleomagnetic Database (GPMDB; http://gpmdb.net/)[38]. Compilations of quality-filtered palaeomagnetic data from the major cratons have also been collated for the Phanerozoic[39] and Precambrian[40]. As evident in these archives, the volume and quality of global palaeomagnetic data are extremely heterogeneous across time and space; both the number and reliability of constraints tend to dwindle backward in time, but the trend is not monotonic (FIG. 2).

Marine magnetics and fracture zones

The primary building blocks for Mesozoic-Cenozoic plate reconstructions are certain physical characteristics of the seafloor, specifically its magnetic anomalies and fracture zones [G]. Magnetic anomaly data from the world's ocean basins record the reversals in the Earth's magnetic field over geologic time, as new seafloor is continuously created at mid-ocean ridges[41] (FIG. 1). They form recognizable patterns of seafloor spreading and, when compared to the geomagnetic polarity timescale [G], can constrain seafloor age. Transform fault and fracture zones trace the direction of seafloor spreading[42] at mid-ocean ridges along small circles [G] and their time-dependent orientation can be used to recognize periods of major plate motion change. Together, magnetic anomaly identifications [G] and fracture zones can be used to determine the age, direction, velocity and, in some cases uncertainty, of relative plate motion through the computation of finite or stage rotations [G] between conjugate plate pairs and the tracing of seafloor spreading isochrons [G] (Suppl. Fig. 1).

Recently, the Global Seafloor Fabric and Magnetic Lineation (GSFML; https://gsfml.earthbyte.org/) repository was established providing a freely available and standardised set of these plate reconstruction 'building blocks'' covering the Mesozoic and Cenozoic (FIG. 2). The continuously updated GSFML contains over 96,000 published magnetic anomaly identifications[43] and a dataset of fracture zone (and other tectonic fabric) traces[44] based on gridded, satellite-derived, vertical gravity gradient (VGG) data[45].

Volcanic products

The idea that chains of seamounts [G] record the (absolute) motion of tectonic plates [G] over long-lived mantle plumes[46,47] [G] has inspired over 50 years of sampling efforts directed at testing this hypothesis. Radiometric dating [G] of volcanic samples yields an extensive set of estimates for the formation age of seamounts. The coherent age progressions along many (though not all) seamount chains, and more rarely along continental trails[48,49], provide evidence in support of the fixed hotspot hypothesis to first order, though evidence also exists for relative motions between hotspots. Observations from age-progressive volcanic trails thus allow plates to be reconstructed backward in time above these stationary or slowly moving hotspots presumably generated by mantle plumes. Seamount ages are available abundantly in the Pacific basin but less so in other basins, and data are everywhere limited by the oldest age of preserved seafloor (FIG. 2).

Massive volcanic outpourings known as Large Igneous Provinces (LIPs) [G] are also thought to result from mantle plume upwellings. The eruption sites of most LIPs correlate spatially with seismically slow structures (and perhaps specifically their edges[50], termed plume generation zones [G]) in the deepest mantle that are imaged by seismic tomography (termed Large Low Shear Velocity Provinces, LLSVPs)[51] [G]. Consequently, the record of older LIPs (preserved on the continents) and other types of deep-sourced volcanism, such as kimberlites [G], provides an avenue to reconstruct the continents relative to the deep mantle[16,17]. The continental LIP record also constrains the configurations and breakup events of ancient continents[52]. Publicly available compilations of these volcanic products include catalogues of age-coded continental and oceanic LIPs and seamounts[53], kimberlites[54] and LIPs through deep-time[16,55].

Geological record

Plate interactions leave many traces in the geological record and are particularly useful for guiding deep-time plate reconstructions. Evidence for ancient convergent margins can be found in records of accreted oceanic and continental material as well as in suture zones, which denote the closure of an ocean basin through subduction[56,57]. Convergent margins associated

with volcanic arcs [G] contain igneous rocks with distinctive chemistries. These volcanic arc rocks form along the margin of the upper (surviving) plate at subduction zones and are therefore preferentially preserved even after subsequent continent-continent collisions that mark the final closure of oceans. Even though these volcanic arcs may be tectonically eroded by advancing subduction zones[58,59], chemically and physically resistant chronometers (such as zircon, apatite and monazite) are preserved in successor basins[60]. It is therefore possible for convergent margin signatures to persist in the geological record for a billion years or more.

Divergent margins preserve characteristic alkalic magmatism [G] associated with syn-rift sedimentary sequences [G] that become buried by passive margin [G] successions. Relics of these are commonly preserved inboard/landward of subsequent plate margins (e.g. the Adelaide Superbasin, Australia[61]). Modern chronological and petrochronological techniques enable identification and interpretation of these sequences, which can be applied to improve the resolution and integrity of plate reconstructions[62]. Evidence for passive margins and former oceanic or back-arc basins can also be found in stratigraphic sequences preserved in orogens that were accreted during subduction or collision (e.g.[56]).

More subtly, geochemical anomalies preserve information about the thickness of volcanic arcs[63–65] that reflect advancing or retreating trenches (or thick/thin arc crust, respectively). Transitions from regular oceanic subduction to subduction of a continental (passive) margin have been interpreted to relate to extensive magmatic flare-ups in the overriding arc[66], which are heralded in the trace element and isotopic record of upper-plate magmas[67,68]. On a larger scale, volcanic arc geochemistry can distinguish between different modes of supercontinent [G] assembly[69,70] – particularly helpful for pre-Phanerozoic reconstructions.

Early 'plate' reconstructions relied on matching fossil occurrences across continental masses[35]. Fossil occurrences can also help with deriving relative age dates of geological units, where other geological information is missing. In addition, established relationships between fossils and their environments can further enrich reconstructions built from lithological records (e.g. climate-sensitive indicators) and the delineation of palaeo-environmental boundaries (e.g. paleoshorelines)[71,72] (FIG. 2).

In order to be useful, geological datasets should include geographic coordinates, age constraints and data-specific metadata. Extensive community compilation efforts have resulted in large, organised databases that meet these criteria. Examples include fossil occurrences (palaeobiology Database, https://palaeobiodb.org/), lithologic indicators of palaeo-climate[73], geochemical[74,75] and rock metamorphism analyses[76], zircon U-Pb age and Hf isotope data[77], and dated ore deposits[78]. The coverage of these databases across time is variable, generally decreasing further back in time (FIG. 2).

Deformation constraints

The history of tectonic plates can be reconstructed (to first order) by assuming that each plate behaves rigidly, with deformation concentrated at its discrete plate boundaries. To second order, geodetic data reveal that around 14% of Earth's surface is presently characterised by more diffuse deformation[79,80] [G] across widened boundary regions. Such regions include both compressional, orogenic belts [G] (Tibet, Andes) and regions of continental extension (western North America, East Africa). Constraining the timing and magnitude of analogous deformation in the geological past is complex at a broad range of length scales, and relies on a diverse range of evidence. Field observations can quantify displacements across faults and indicate the direction and timing of displacements. Further evidence for the timing of deformation can be retrieved from stratigraphy and low-temperature thermochronology [G], while palaeomagnetic data can reveal tectonic rotations. Piecing together these observations allows for the sequential restoration of deformation back through time, both along transects and in 2D map view[81–84].

Vast areas of stretched continental crust formed during Pangea rifting[10,85] are now typically submerged or covered in younger sediments. The total amount of stretching since rifting began can be estimated from present-day crustal thicknesses (e.g. from seismology or gravity inversion). The time-dependence of deformation can be reconstructed by sequential restoration of interpreted seismic reflection data and analysis of basin subsidence patterns[86], and by integrating constraints on permissible

plate motions from regions outside the deformation zone itself[87–89]. Compressional regions, on the other hand, can be restored using crustal shortening estimates[57].

Palaeo-surfaces in the mantle record

The Earth's mantle is the vast rock and heat reservoir from which tectonic plates are generated at mid-ocean ridges, and to which they are recycled in subduction zones. Seismic tomography [G] can image these reservoirs of lithosphere creation and destruction *in situ*, in principle at all mantle depths (FIG. 1). Local variations in seismic wave propagation essentially reflect temperature anomalies, at least below lithospheric depths. Seismically fast regions translate to downwelling 'slabs' of cold, sinking lithosphere, while seismically slow regions point to hot, buoyant upwellings ('plumes'). Slabs represent subducted palaeo-lithosphere, which motivates the use of mantle structure for plate reconstructions back in time.

Seismic tomography models are becoming accessible to non-specialists through open access portals permitting their interactive display, analysis and comparison97,98. The interpretation of slabs as palaeo-seafloor related to palaeo-trenches has progressed in lockstep with tomographic image resolution. Early normal-mode tomography inferred the longevity of Pacific rim subduction[90], based on massive lower-mantle slab assemblages. Well-resolved regions of slab piles, from P-wave tomography, allowed for correlation with onshore orogenic and/or seafloor isochron records[91–95]. Subsequent P-wave imaging supported the inference of palaeo-trench locations over geologic time[96–102] the 'unravelling' of slabs to their palaeo-basins for budget analyses[103,104] and the proposition of a global slab-based mantle reference frame[96]. Such predictive uses of slabs frequently challenge geologic interpretations of palaeo-trench locations. A conceptually logical but technically challenging next step is the integration of slab-inferred palaeo-trenches into global models with continuously closing plate boundaries[107–110].

Geodynamic constraints and assumptions

Even considered jointly, the various observational records will only provide incomplete constraints of plate tectonics on Earth. In order to fill observational gaps in space and time, particularly in deeper time, assumptions must be made that represent a simplification of more complex geodynamic processes; a uniformitarian view of geodynamic processes over time. Some examples include the approximation of fixity of mantle upwellings[16], stability of the GAD through time[37], and limits on the rate of motion for plates and plate boundaries[111]. Thus, although 'reconstructions' are primarily based on 'data', they must necessarily also incorporate assumptions of how the world works.

In another context, geodynamic model output is sometimes used as a core part of the plate reconstruction process and thus can be considered as another 'data' type. Examples of these include geodynamic models that hindcast the motions of hotspots[112–114], or the development of optimised absolute reference frames[111]. These approaches couple a plate reconstruction with a geodynamic model; these dependencies should be borne in mind when using and modifying such reconstructions.

Types of plate reconstructions

Innovations in software, workflows and methodologies, and the ability to integrate new data sources have driven advancements in plate reconstruction modelling that move beyond the early 'continental-drift' type reconstructions. These advancements include: plate-focussed reconstructions; reconstructions incorporating diffuse deformation; and mantle-informed reconstructions incorporating knowledge of palaeo-trench locations ('tomotectonic' models). Each model type has a purpose depending on the research question being considered and therefore has value in its own right.

Continental drift-style reconstructions

'Plate' reconstructions in the decades following the plate tectonic revolution, especially palaeomagnetic-based reconstructions of times predating Pangea, were typically made in a framework that (ironically) resembled continental drift: continents and terranes were reconstructed through time as isolated crustal blocks (FIG. 3). Many of these models reconstructed a singular moment in the geologic past, and those that represented a temporal evolution were often presented as a series of static reconstructions at discrete, widely spaced time intervals. Consequently, the movement of crustal blocks in between time-steps

was only indicative, sometimes implying physically improbable transitions, or movements inconsistent with the implied plate boundary configurations[115]. Models were not readily testable or reproducible because no finite rotation sequences were reported. Nevertheless, given the tools available at the time, these models were incredibly valuable and laid the foundation for the next generation of models.

Motivated by the desire to move away from these 'continental drift' type reconstructions and towards quantitative reconstructions, a new suite of models tied to finite rotation sequences that integrated knowledge from the seafloor spreading record were developed[5,9,116]. In some instances, reconstructions may have had time-evolving 'plate' features displayed, such as the location of selected plate boundaries and/or plate velocities[117–119]. These reconstructions were an important methodological advance as they considered plate tectonics principles with an underlying kinematic model. However, they suffered from an incomplete network of plate boundaries and/or time-steps that were too far apart for a meaningful assessment of the full time-varying evolution of their particular area of interest.

Plate-focussed reconstructions

The natural progression in model developments was to build plate-focussed reconstructions, which fully account for the evolving nature of plate boundaries through time via a series of continuously closing plate topologies [G][120](FIG. 3). These models present a continuous spatio-temporal framework of surface plate motions that can be directly interrogated or coupled to geodynamic models of mantle convection. A key requirement of plate-focussed reconstructions is a global kinematic model, underlain by a combination of the main data types outlined earlier, that describes the relative motion between plates and/or their motion with respect to an absolute reference frame. The motions of subduction zones are tied to overriding plate motions through polarity assignments and mid-ocean ridges are reconstructed using the rotation of the neighbouring diverging plates.

These plate reconstructions were initially global in scope, focussed on the Cenozoic and Mesozoic where the seafloor spreading record was the primary constraint[7]. Through interrogation and integration of palaeomagnetic and geologic records, these models are now being pushed back into deep time, before the origin of preserved ocean crust[121–124]. Detailed regional models have also been developed within a global framework[125–128], many of which have subsequently been incorporated into global topological models[129].

Deforming plate reconstructions

Traditionally, reconstructions consider tectonic plates as rigid features. The framework of rigid plate tectonics presents one avenue to represent crustal deformation[130] - the deforming continents are divided into discrete blocks, bounded by major faults, with distinct kinematic histories. This approach provides a useful first approximation for intra-continental motion, and global reconstructions have long incorporated this concept, for example to reconstruct the opening of the South Atlantic[131,132]. Representing deformation this way results in gaps and overlaps between individual rigid blocks back in time[84] and limits the usefulness of rigid-block reconstructions to reconstruct palaeogeography and palaeoelevation in regions with complex tectonic histories[72].

An alternative approach is to define parts of the Earth's surface as regions of continuous deformation[130]. The kinematics at any location within deformation zones is interpolated from nearby points with known displacements both within and at the boundaries of the deforming region[133] (FIG. 3). Tools to construct continuum-style models of deformation have recently been added to *GPlates*[15], spurring the development of deforming reconstructions at regional and global scales[10,83,134]. Compared to rigid block models, they involve a greater computational burden since reconstructing each point requires integrating motions across a series of discrete time intervals (the length of these intervals being a trade-off between speed and accuracy). Advantages over rigid block models include the ability to generate continuous models of evolving crustal thickness or basin subsidence over time, and the ease of visualising the spatial distribution of strain at individual time instances (FIG. 4A). This approach is in its infancy and further developments, such as subdividing between intraplate and accretionary orogenesis, would improve these types of reconstructions.

Tomotectonic reconstructions

By constraining palaeo-trench locations and the volumes of subducted seafloor, seismic tomography has recently enabled some fundamental advances in quantitative plate reconstruction (FIG. 3). This information, which can be inaccessible from surface records, is highly complementary to magnetic isochron-based reconstructions that primarily constrain seafloor spreading information. Advances have been driven by the confident resolution of regional slab-scapes into segments on the scale of individual palaeo-arcs (1,000-3,000 km long, 300-700 km wide slabs), across all mantle depths. These advances have been applied by using slabs, among other constraints, to place palaeo-trenches into fully kinematic models[108–110,135](FIG. 4B).

Palaeo-trench inference is subject to uncertainties and ambiguities, especially for slabs no longer connected to active subduction zones. Ongoing debate concerns the extent to which present-day slab geometries reflect absolute palaeo-trench geometries, as opposed to later deformation or translation inside the convecting mantle[92,101,136–138]. Given the current uncertainties in mantle rheologies, mantle-informed (i.e. tomotectonic) reconstructions effectively have to propose slab deformation hypotheses, from which trench placement principles can be derived; their predicted trenches may then be evaluated against all pertinent, observational records[92,96,101,103,104,138,139], much like the geodynamic constraints and assumptions outlined earlier. Results point towards substantial slab thickening, slow sinking rates, and little lateral displacement, so that slabs seem to faithfully preserve *absolute* palaeo-trench locations up to and perhaps beyond 300 m.y.[92,140] into the past. This offers the prospect of a slab-based mantle reference frame[96], with the quantification of mantle rheologies as a potential, valuable by-product[96,137]. Debates remain whether some slabs segments were dragged inside the mantle by 1000-2000 km[141–144].

Applications

At its most basic level, plate reconstructions provide the framework for determining the location of features on the surface of the Earth through geological time, like a deep-time GPS system. The history of plate motion is intimately linked to the evolution of both solid Earth processes, and environmental change at Earth's surface. Tectonics shapes the distribution of continents and oceans, the elevation and location of mountain ranges, the eruption of massive and widespread volcanism and the opening and closing of oceanic gateways [G][145–148]. These changes over time dictate the physical circulation and chemical composition of the ocean and atmosphere and govern the distribution of terrestrial and ocean biomes[149–152], with implications for understanding modern and future planetary changes[153].

Spatio-temporal analysis

Geoscientists are typically fascinated by the idea of looking for patterns in the geological record, and testing hypotheses for what processes control them. The integration of global reconstructions, databases with age-coded geological information, and the software infrastructure to tie them together, is a powerful enabler for the discovery of new insights. For example, plate configurations underpin studies examining changes to Earth's biodiversity, evolution of organisms and contributors to extinction intensity[26,154–156]. The processes that influence the present distribution of economically important mineral systems can be evaluated by examining where they form in relation to deep-Earth structures and plate boundary kinematics[28,157,158] (FIG. 5A). Links between palaeogeography and climate have been quantified by mapping the distributions of lithological climate indicators[71] and LIP eruptions[53,159], and arc-continent collisions[160]. Geodynamic drivers of long-term sea-level can be estimated from reconstructions of past ocean configurations[116,161,162].

A key characteristic of plate-focussed reconstructions is that they are greater than the sum of their constituent constraints. While the location and sense of motion along plate boundaries can often be determined through the unification of geophysical and geologic data, detailed budgeting of the rates of motion (and thus material fluxes) is rarely directly determinable from these data. However, in being bound to a spherical surface of constant area, global plate motion reconstructions must necessarily balance such fluxes, and so provide readily retrievable estimates of them (FIG. 5A). Although this is a vast and still largely untapped potential, estimations of these boundary fluxes have found applications in understanding fluctuations in atmospheric CO_2[163,164], the frequency of magnetic reversals[165], the age distribution of zircons[166,167], and geochemical signatures[32,168–171], among a rapidly expanding list of other applications. Advances in code development and formalised data-mining and data

visualisations, such as the development of Python-based extensions to GPlates (pyGPlates), are helping to quantify the strength of associations found in the geological record.

Geodynamic studies

Reconstructing plate motions is a fundamental step towards understanding what drives these motions, the nature of the plate-mantle system, and how this system may change over geological time[172]. Indeed, a primary motivation for developing plate-focussed, topological reconstructions has been to couple them with geodynamic models exploring these issues (FIG. 5B). Nonetheless, plate-focussed reconstructions have themselves become an important tool in characterising the behaviour of tectonic plates and their boundaries through geological time[61,85,164,173–177]. These reconstructed characteristics can be compared to numerical models that use physics-based solutions of mantle convection, which generate plate-like behaviour[178–182]. Reconstructions can also provide a basis for quantifying the forces that drive the plates themselves, such as those associated with the history of subduction and evolving lithospheric structure[20,183].

An alternative approach seeks to assimilate information from reconstructions directly within a dynamic modelling framework[184–186]. In these models, reconstructions provide the basis for defining the locations of subducting slabs, deep mantle upwellings, and evolving lithospheric structure through time (FIG. 5B). Coupling this knowledge with numerical models of mantle convection yields time-dependent estimates of mantle structure and dynamics. New insights are gained by examining the success or failure of models in explaining geological observables and have provided clues as to the nature of plate reorganisations[187,188], the time-dependence of large-scale mantle structures[17,19,189,190], interactions between plumes and plates[191], subduction dynamics at different depths[18] and mountain building processes[192]. These models can also provide predictions of the vertical motions of Earth's surface induced by mantle flow (dynamic topography[193]) and how these motions may have shaped Earth's topography and cryosphere at a range of spatial and temporal scales[194–198].

Deep-time Earth System Modelling

Global plate reconstructions provide a link between long-term solid Earth processes and surface environments. An alternative to investigating these links through data-driven approaches (as discussed in the Spatio-temporal analysis section) is to use spatially-resolved models of the Earth's surface (paleogeography + elevation) as critical model boundary conditions in Earth System Models (ESM) [G] (FIG. 5C). Until recently, most deep-time ESMs have focussed on discrete times in Earth's past, due to the significant effort required to generate palaeo-elevation reconstructions, and in some cases to run the ESMs themselves. These 'snapshot' models, which can simulate past ocean and atmospheric circulation patterns, biogeochemical cycling or map habitats, have been used to investigate a range of global-scale chemical, biological and climate changes and their drivers[199–205], with applications to present-day[206].

With advances in computational power and new software, it is now possible to use spatially explicit ESMs in a more continuous way across long-periods of Earth history[24]. These models quantify the feedbacks, both positive and negative, between plate tectonic reconstructions and the chemistry and physical structure of the atmosphere, hydrosphere and biosphere in deep-time. While still in its infancy, various flavours of ESMs have been used to: demonstrate that sporadic ocean anoxia in the Mesozoic was caused by restricted ocean circulation and volcanism[207]; illustrate that tropical continent-continent collisions helped plunge the world into an icehouse[23]; highlight the major role of plate tectonics in driving tropical marine shallow reef biodiversity[25]; and been used for important proxy model-comparisons[24,208]. Plate models that extend into deeper time (e.g. back into the Paleozoic114 and Precambrian116) present opportunities to explore ESMs further back in time.

Education and outreach

The plate tectonic modelling infrastructure described so far has traditionally been developed by, and for, academic researchers and industry. However, the easy accessibility of community-driven tools and increase in data sharing is inspiring a new user-base in geoscience education and public outreach. Digital tools possess powerful capabilities for visualising and integrating

geospatial data through time, while also communicating challenging ideas and concepts that can otherwise be difficult to grasp (e.g. the vastness of geologic time and large-scale plate motions on a spherical Earth).

Teaching plate tectonic concepts requires students to think and learn in four-dimensions, at scales outside the comfort zone of intuition and everyday experience. It also encourages a 'systems thinking' approach, integrating information from different disciplines to understand the whole Earth system (e.g. connection between plate motions, convection in the deep-Earth and movement of ocean currents). When faced with these sorts of challenging concepts, student engagement and comprehension is aided by the use of digital tools[209,210] and open-data. Early continental drift type reconstructions[34] and more recent examples using GPlates[33] are demonstrating the benefits of these resources in geoscience education, which can be complemented with other developing educational innovations.

On a societal level, communicating how the Earth system has evolved through deep-time informs public discourse at a time when there is a heightened awareness of the ever-changing nature of our planet. While these visualisations have always found a place in public spaces, such as museums and planetariums, the popularity of online virtual globes and portals[105,211,212] are making them more accessible to the public than ever before, thereby contributing to a more scientifically literate public.

Guidelines on Best Practice

In light of the methods, data and example applications detailed above, a set of basic guidelines are outlined with the aim of helping non-specialists to both understand the decision-making process involved in generating plate tectonic reconstructions and to highlight areas to consider when using and interpreting them.

All models are wrong

A theme pervasive within the discussion to this point is the blurring of the boundary between 'models' and 'data'. Many researchers consider the kinematic reconstructions themselves as 'models', designed to explain geological and geophysical data together with some underlying assumptions that simplify the true complexity of the dynamic Earth. At the same time, other communities consider reconstructions as 'data' to be assimilated into ever more sophisticated simulations (their 'models') of the Earth system. Either way, it is important to consider the many ways tectonic reconstructions simplify reality when seeking to draw meaning from them.

The increasing sparsity and decreasing fidelity of data constraints back in time (FIG. 2 and 6) means that in deep-time, less complex reconstructions are required and appropriate to explain the available constraints. In terms of plate motion change, the highest-resolution records of seafloor spreading document changes in late-Cenozoic relative plate motions at close to 1 Myr resolution[213]. While such records are increasing, they remain limited in space and time, and building global reconstructions that capture the complete record of plate motion change recorded by polarity reversals remains a goal for the future. Current global reconstructions typically contain a coarser temporal sampling of both relative and absolute motions applicable on a global scale, with plate motions recorded at timescales of 5-10 Myr during Pangea breakup, and coarser still for older times when palaeomagnetic data are the only quantitative constraints. This invariably means some plate motion changes are not captured in global models or they are captured but rendered at the model time interval rather than when the change occurred.

The coarse resolution of most global plate reconstructions at least partly explains the decreasing number of distinct plates defined within global full-plate models further back in time (FIG. 6). Although it may be the case that a smaller number of plates would be expected during times of supercontinent assembly, geodynamically there is no reason to assume consistently fewer plates in the geological past. For plate reconstructions spanning more recent times (e.g. past ~160 Myrs) there has been a significant increase in the level of detail (in terms of the number of rigid plates) incorporated into global reconstructions (FIG. 6). The newly-modelled plates typically lie in tectonically-complex regions close to subduction zones, taking advantage of improvements in tomographic imaging outlined above, and in mapping orogenic processes. These regions remain the subject of ongoing research, particularly in the reconstruction of back-arc basins prior to the mid-Cenozoic, known to be poorly

constrained[161], and the geological history embedded in accretionary margins[109]. Deforming plate models remain in their infancy, as do full-plate reconstructions of pre-Pangean times, and the future holds vast potential for improvement through the collection of new data, to the development of new methods, to improved data-assimilation in the reconstruction process.

When using reconstructions as 'data', it is crucial to keep in mind the underlying assumptions of different reconstructions, and the distinction between those aspects of global models that are well constrained by data and those which are interpolated or extrapolated. For example, interpretations based on reconstructions of 'lost' (fully subducted) oceanic plates must consider that much or all of their kinematic histories are extrapolated under simplifying assumptions, such as spreading symmetry and the minimization of plate speeds. A particularly notable case-in-point is the massive 'Panthalassa' (palaeo-Pacific) oceanic domain– commonly modelled as a triad of large oceanic plates centered around a persistent ridge-ridge-ridge triple junction, and with fixed absolute plate motions decoupled from the global plate circuit. When it comes to deeper-time reconstructions, many plate motions are extrapolated from a limited number of palaeomagnetic data widely spaced in time and guided by geological interpretations of past plate margin configurations. Another consideration is that individual global reconstructions can only capture one of many candidate models for a given region of space and time. The chosen model represents a decision made by the model builder based on their objectives in designing the global model, limited by the constraints available.

Rather than placing limits on the use of global plate reconstructions according to all these sources of uncertainty, embracing the uncertainties in presently available reconstruction models provides an immense opportunity for hypothesis testing aiming to improve on the current state-of-the-art, for example through novel model-data comparisons[17,71,99,214,215].

No 'one-size-fits-all'

Plate tectonic model builders are frequently asked "which model should I use"? The simple answer is: there is no 'one-size-fits-all'. The many applications outlined thus far use a range of different reconstructions (and in many cases, compare results for a suite of models), with the best choice depending on the purpose of the study and the research question being addressed, with a primary aim being to avoid circular reasoning. Each plate reconstruction is based on a combination of data types and techniques usually designed for different time periods, resolutions and objectives. For example, a reconstruction model with well resolved relative plate motions is required for a study focussed on plate driving forces , while studies exploring deep-Earth dynamics are most concerned with the choice of absolute reference frame and continuously-defined plate boundaries. Reconstructions in the context of palaeoclimate and palaeoenvironmental indicators require a palaeomagnetic-based absolute reference frame[212].

Likewise, when developing a plate tectonic reconstruction, there is no universal, objective hierarchy of the tools, methods and data sources to be employed, and in many cases the relative importance or usefulness of a given set of tools will change across space and time even within the same model. Part of the process is to consider all the available evidence and to weigh it against each other, while acknowledging that it is not uncommon to find complementary data providing seemingly contradictory answers. For example, although magnetic anomalies in the ocean basins are the preferred data to reconstruct the Mesozoic-Cenozoic ocean basins, some magnetic anomalies are uncertain and can lead to erroneous interpretations of plate motion (e.g. Australia-Antarctica break-up[89]). It is therefore critically important that the model-maker carefully document the (often subjective) decisions about which data are being relied on and why. Equally, if using a published reconstruction, understanding the critical decisions underlying that particular model is important.

Follow the 'rules'

Observations of solid-Earth processes at present-day and in the more recent past provide a framework of tectonic and geodynamic principles to inform the building of regional and global plate models further back in time. These observations can be converted into a set of 'rules' that can be followed by the model builder particularly when generating or validating deeper-time plate models where interpolation and extrapolation of limited observations is most necessary.

In any plate model, divergence between plates should occur at mid-ocean ridges and continental rifts, convergence at subduction and collision zones, and strike-slip motion along transform faults. These plate boundaries should evolve self-consistently through time; mid-ocean ridges should be broadly perpendicular to small circles about the Euler pole describing the relative motion between the two diverging plates, and transforms should be parallel to these small circles. Unlike mid-ocean ridges, continental rifts open at a variety of oblique angles[216]. Breaking strong, thick oceanic lithosphere is hard (relative to rupturing young, thinner lithosphere) and should occur infrequently. Subduction initiation, fundamental to the plate tectonic cycle, occurs under limited conditions[217] Changes in plate boundary configurations should only be modelled when supported by data or under tectonic scenarios known to be related to plate boundary readjustments (e.g. subduction polarity reversal induced by plateau collision or ridge jumps and microcontinent isolation as a consequence of ridge-hotspot interaction).

Other behaviours can be quantified and used as a guide where limited evidence is otherwise available to constrain plate kinematics. Oceanic plates typically move faster than continental plates; since Pangea breakup oceanic plates have reached speeds of 20 cm/yr whereas continental plates generally do not exceed speeds of 10 cm/yr[218]. Large plates typically move slower than small plates[218], and plates bounded by subduction on at least one edge tend to move faster than those surrounded by mid-ocean ridges, due to the influence of slab pull. Cenozoic reconstructions indicate that trenches dominantly retreat rather than advance, with migration rates rarely exceeding 3 cm/yr[175]. Recognition that changes in plate-motion typically occur on timescales no shorter than a few million years allows plausible plate motion histories to be derived from noisy observations[219]. For a further description and discussion on parameters that can be used to generate geodynamically plausible motions, see ref[220].

Know your 'data'

Each plate tectonic reconstruction requires a rotation model, which presents a set of finite rotations describing the time-dependent motion of each plate in the model. Each plate is defined by a unique user-defined plate identification number (plate ID). These plate IDs can (and do) vary between models, making it essential to ensure consistency between the plate IDs assigned to data to be reconstructed - particularly when comparing a dataset across several alternative plate reconstructions. A lack of consistency will lead to data not moving through time, or following the rotations of an unrelated plate. The choice of absolute reference frame and of plate circuits [G] creates further dependencies that also dictate error propagation in the rotation model, and need to be carefully considered (BOX 1).

Another important consideration is the timescale. Timescales are an immensely complex 'product' in themselves: a negotiation between many (often sparse and sometimes contradictory) data types, and methods (e.g. biostratigraphy, magnetostratigraphy, geochronology, cyclostratigraphy). Plate tectonic models require a timescale to be selected as a 'data' input yet timescale creators would view it as a 'model', with expected differences from one timescale to another. While plate tectonic reconstructions do contain data tied to absolute ages, the choice of timescale is particularly important for aspects of the model created using the seafloor spreading record or stage boundaries. For example, the age assignment of the Barremian-Aptian boundary (or M0) has varied by over 5 Myrs in the space of a decade[221]. Changes of this scale can affect the interpretation of results and even the conclusions of a study, such as the mid-Cretaceous seafloor spreading pulse in the Pacific[222]. On a more practical level, timescale consistency between data and the reconstruction model should be ensured.

Animate and integrate

As described, plate reconstructions with evolving plate polygons have opened new avenues of research in spatio-temporal analysis and geodynamic modelling, but have also proven to be a powerful plate model validation tool. When designing plate models, it is far better to create a continuous, kinematic plate reconstruction with rigid seafloor that grows and is destroyed, and plate boundaries that move dynamically and continuously, than to rely on snapshot models or cartoons. Even if some parts of the model are speculative, a kinematic and geodynamically plausible model, guided by the rules outlined above, demonstrates that the idea 'works'. In contrast, models that seem plausible in discrete snapshots can fail to work kinematically and therefore

can be discarded. Further to that, we can be more confident in regional reconstructions when they are successfully integrated within a global tectonic framework.

Designing increasingly complex plate models that generally adhere to the plate tectonic rules mentioned above is challenging. It requires an iterative approach, which involves a back-and-forth model validation/adjustment phase before settling on a final product. Animations of plate tectonic reconstructions using tools such as GPlates are integral to this phase. However, our ability to integrate an ever increasing amount of complex data, and their uncertainties, requires innovative ways to illustrate the reconstructions within the context of these new data, which poses an even greater visualisation challenge.

Consider uncertainty

Considering the dizzying array of data and subjective interpretations required to build global reconstructions, quantifying the uncertainty is complicated. Where reconstructions are based on long-established methods (e.g. magnetic anomaly identifications, palaeomagnetic data, hotspot trails), the geoscience community has developed fairly standard ways to report raw data, their interpretation, and the reliability of those interpretations[223–225]. For newer approaches, such as building tomotectonic or deforming plate reconstructions, the practices of uncertainty quantification are still evolving.

Once all the observations are combined into a single 'best-fit' model, the uncertainty in the end result is, for want of a better word, uncertain. However, we can characterise the likely magnitude of uncertainties and how they vary in space and time (FIG. 6). Earlier estimates of the total uncertainty budget in reconstructed locations are estimated to within 500-1000 km for the last 100-200 Myrs[117,226] - but uncertainties generally increase back in time, and depend on changing plate configurations. For example, the position of a small continental block like North China may be less certain when isolated from all others, as compared to younger and older times, when it may have been connected to larger landmasses that provide additional constraints (FIG. 6).

A useful strategy for 'end-users' is to focus on the questions we can pose rather than the reconstructions themselves (see ref[227] for a useful discussion). In this way, we can assess whether the conclusions we seek to draw would be influenced by even the most pessimistic estimates of how wrong the reconstructions are likely to be. For example, the choice of reconstruction and uncertainties in defining continent-ocean transitions are unlikely to change any inferences on the nature of continental rifting and break-up[85,216]. On the other hand, studies linking high-resolution seafloor-spreading records with estimates of plate driving forces provide a pathway to distinguish between motion changes that are geodynamically plausible, and those that likely reflect 'noise' in the reconstruction basis data[219].

Recognise the value

In spite of these cautionary notes, state-of-the-art plate reconstructions have transformed how geoscientists are able to work and interpret their data and should be recognised for the value they bring. The current generation of open-access, global full-plate reconstructions provide the framework, and common language, to begin working in a genuinely integrated way across disciplines, and in truly deep-time. They should be considered both as a starting point and a point of comparison on which future studies can build. That is to say, no plate model will ever be true but limitations in these models should spur further development, which ultimately helps to drive new discoveries.

Summary and future directions

Since the early global plate reconstruction 'flip-books'[226], geoscientists have seen the extraordinary value of conceptualising their ideas in space and time (i.e. in a framework provided by a plate model). With the advent of community-driven, open-source software and tools, plate models have become accessible and practicable to the wider geosciences community. With this accessibility comes a responsibility for specialists and non-specialists alike to understand how these plate models are built, their weaknesses and pitfalls, and how they can be used effectively to ensure correct inferences are made. This can form the

foundation for the building, as a community, of a virtual Earth ecosystem, which can integrate knowledge from the deep-Earth to the surface, and from deep time to the present-day, in order to explore the bio-, geo- and chemical evolution of the planet.

Further advances in plate tectonic model development will benefit from the collection of new data focussed in key regions and time periods. Geological samples and geophysical data from the oceans remains sparse, particularly in areas far from large human population centres (e.g. western Pacific, southern high-latitudes, East Pacific Rise). These gaps in our knowledge warrant extra effort directed toward data collection, for example through continued support of the International Ocean Discovery Program (IODP), and the promotion of novel ways to acquire data more cost-effectively (e.g. UAVs and remote sensing). On land, the collation of key paleomagnetic data targeting spatial and temporal gaps (e.g. Fig. 2) together with expanding geological datasets are helping resolve long-standing unknowns concerning the positioning of continental blocks, thus enabling the development of deeper-time reconstructions. Continuous innovation in new geochronology and geochemical techniques will progressively unlock previously trapped information about the origin and evolution of a rock sample (and the tectonics associated with it), thereby driving new discoveries even without the requirement of new sampling campaigns.

The acquisition and analysis of new data should be complemented by the curation and improved accessibility of existing datasets under structured, community driven databases that follow the FAIR data principles. Great strides have been made by many fields in the geosciences but improvements can be made in some areas[228]. This cannot be achieved alone and requires investment in national research infrastructure programs across countries, such as EarthCube (https://www.earthcube.org/) and AuScope (https://www.auscope.org.au/),. These infrastructures range from data collection to model development to data curation.

Progress towards turning this wealth of data into knowledge through data-model integration has been facilitated through continuous plate-based reconstructions and the workflows developed through GPlates. New avenues for discovering patterns and associations in data and between suites of models come from machine learning and data science techniques. Important challenges come with placing these increasingly complex and multidimensional models together with assimilated datasets within an uncertainty framework (see Constraining Uncertainty section). Such problems can only be solved through collaborative efforts that meld expertise from emerging fields of data science with the depth of existing knowledge in the Earth Sciences. . . Training the next generation of geoscientists who can push the field of plate tectonics further should focus on the development of skills spanning geology, geophysics, and computational methods and the mindset of multidisciplinary research.

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Related links

MagIC: https://www2.earthref.org/MagIC

Global Paleomagnetic Database: GPMDB: http://gpmdb.net/

GSFML: https://gsfml.earthbyte.org/

Palaeobiology Database: https://palaeobiodb.org/

EarthCube: https://www.earthcube.org/

AuScope: https://www.auscope.org.au/

Competing interests

The authors declare no competing interests.

Author contributions

MS conceived the work and led the writing of the manuscript. SEW led the production of the figures. All authors contributed to the writing and reviewing of all components of the manuscript.

Data availability

GPlates is open source software and can be downloaded at https://www.gplates.org/. All data and plate models shown in the figures are publicly available and can be found in the publications quoted in the text. Python workflows to create the figures will be uploaded to zenodo.

Figure captions

FIG. 1. Features and data types used in plate reconstructions. Cross-section of the plate and mantle system across the eastern Pacific, South America and South Atlantic. The surface layer includes the age of the ocean floor[230], constructed with magnetic anomaly identifications and seafloor fabric, which are used to derive plate motions based on the seafloor spreading record, draped over seafloor bathymetry[45] in the oceans. The surface layer of the continents displays the geological provinces[80] highlighting orogenic belts and other convergent margin features (grey), rift basins (blue), cratons and shields (pink), and volcanic provinces (red). These geological datasets constrain plate boundary locations and areas of deformation, and in the case of volcanic provinces, absolute reference frames. Depth sections show the seismic tomography model DETOX-P2[140] corresponds to lateral temperature anomalies in the mantle where blue areas indicate cold, negatively buoyant material (e.g. subducted slabs) and red indicates hot, buoyant material (e.g. plumes and LLSVPs). Plate boundaries from[129] in yellow. Figure generated in GPlates. This figure highlights the various features and data types that are routinely used in the construction of plate tectonic models.

FIG. 2. Data availability through time. Plots that quantitatively display the number of data points for various data types used in plate reconstructions through time. Data sources from top to bottom include: magnetic anomaly identifications[43] (noting the absence of the Cretaceous record due to the Cretaceous Normal Superchron), fracture zone segments[44,231], seamount trails[39], palaeomagnetism[232], lithologies[73], palaeobiology data (from https://paleobiodb.org), rock geochemistry[74], zircons[77], metamorphism[76], ore deposits[78], geological events[55,233–235]. These plots highlight periods in Earth history with more abundant data constraints compared to periods with a paucity of data, noting that these do not decrease monotonically for all data types through time.

FIG. 3. **Plate tectonic reconstruction types.** a: continental drift type reconstructions are limited to the movement of continental blocks and terranes, as illustrated with the plate model of[124]. b: plate tectonic focussed reconstructions include a model of plates (coloured with transparent fill), plate boundary evolution and plate velocities (small black arrows), as illustrated by the plate

model of[122]. c: tomotectonic reconstructions infer the history of subduction from seismic tomography images to place the locations of subduction zones through time, as illustrated with the plate model of101. :[10]. d: deforming reconstructions additionally include zones of active deformation, as illustrated with the plate model of8 This figure showcases the four main types of plate tectonic reconstructions discussed in the text and the various information that can be computed from these models (e.g. plate velocities in the case of plate-focussed reconstructions and contraction/extension for deforming plate models) or the main data input into the models (in the case of tomotectonic models).

FIG. 4. Regional example showcasing latest advances in plate tectonic modelling. a: reconstruction of Cenozoic deformation, at 35 Ma, along western North America and South America where preserved ocean floor is plotted as grey shading, subducted ocean floor as solid dark grey and crustal thickness estimates derived from the deforming model on the continents. The solid yellow line denotes the outer boundary of the deformation zone and white lines are plate boundary networks. Insert figures show the evolution of the Andean margin according to the deforming model of74 and plate motions along western North America according to the deforming model of73. b imaged subducted slab material from seismic tomography (coloured blobs) along western North and South America at 100 Ma and their relationship to reconstructed palaeo-ocean basins (labelled) according to[109]highlighting the tomotectonic reconstruction approach. White lines denote plate boundaries. Basemap figures generated in GPlates. This figure highlights the two most recent advances in plate tectonic modelling appraoches, deforming and tomotectonic models, as applied to North and South America.

FIG. 5. P**late tectonic modelling applications.** a: an illustration of the reconstructed subduction history along the Andean margin as a plate kinematics and data mining example. Plots illustrate (i-ii) the potential link between overall subduction flux and zircon age frequency, with a time lag[166]; and (iii-v) the along-strike variations on inputs to the subduction zone and how these could relate to porphry copper formation[30]. Kinematic parameters based on[10] and thickness of subducted sediments from[236]. b: example of palaeogeographically-constrained geodynamic output, showing deep mantle temperature anomalies and surface dynamic topography at 180 Ma[220]. c: example of climate model output derived using palaeogeographically reconstructed boundary conditions. Colours show the sea-surface temperature[237] in the oceans, and Koppen climate classes on the continents[238]. This figure provides examples of how plate tectonic reconstructions can be applied in for spatio-temporal analysis (a), geodynamic modelling (b) and ESMs (c).

FIG. 6. Uncertainty demonstration. a: shows how the distribution of land would influence preservation bias amongst data especially as a function of latitude through time[239]. b: smaller blocks like North China will be less well constrained and have higher uncertainty than those with more data and which have been attached to other units[239,240]. c:the number of (modelled) plates decreases back in time in two different reconstruction models (refs[7,124]). This apparent decrease could be partly 'real' (e.g. less plates during a period of supercontinent aggregation), and partly a function of more detail being added to the models over time. d: the total length of (modelled) global subduction boundaries are much greater than the length of continental subduction boundaries (as reflected through arcs) preserved in the geologic record[241]. The total of subdcution boundaries is a closer match to the length of subducted slabs inferred from seismic tomography[163] which would include all arcs including 'lost' intra-oceanic arcs, though the trends between the restored tomography and plate reconstructions are different over time. e: reconstructed oceanic crustal production through time based on (adapted from ref.[124] and in particular where this is constrained by preserved seafloor (bright, solid polygons) and where no seafloor is presently preserved (faint dotted polygons). Estimating uncertainty in plate reconstructions is difficult but this figure seeks to demonstrate some of the sources and magnitudes of uncertainty using various 'data' and model output.

Text boxes

BOX 1: Guidelines on choosing an absolute reference frame

The motion of a plate can be described relative to another mobile object (e.g. another plate) or relative to a 'fixed' system of reference. The latter motions, called 'absolute' motions, can be assembled into absolute plate motion (APM) models (see[9]).

Importantly, alternative APM models imply different 'absolute' motions. The most common include the 'paleomagnetic reference frame' (anchored to the planetary spin axis) and the 'mantle reference frame', to which hotspot- and tomographic-based reconstructions belong. . The paleomagnetic and mantle reference frames differ from one another due to the phenomenon of true polar wander (TPW), which rotates the solid Earth relative to Earth's core (where the magnetic field is generated); the palaeomagnetic reference frame thus remains fixed to the spin axis during TPW (according to the GAD hypothesis).

Different APM reference frames are applicable for different purposes. For studies with an emphasis on paleoclimate or paleobiology [Fig 5c], the palaeomagnetic reference frame [A]--which ties plate positions to paleolatitude–is usually the most appropriate. For studies of the plate-mantle system [Fig 5b], a mantle reference frame is preferred, whichreconstructs seamounts above mantle hotspots [B], or ties paleo-subduction zones to slab remnants mapped by tomography [C]. As hotspot-based and tomotectonic reconstructions are limited to the last ~130 and ~300 Ma, respectively, the continuation of mantle reference frames into deeper time requires the adoption of significant assumptions. One approach is to correct the paleomagnetic reference frame for TPW and to estimate palaeolongitudes by the reconstruction of LIPs and kimberlites to the Plume Generation Zones around the LLSVPs[242] , [B] by assuming that the LLSVPs have remained fixed. In practice this mandates an iterative approach, as estimating palaeolongitude and TPW are convolved problems[16]. Another approach attempts to optimise the kinematic characteristics of plates and plate boundaries [D] according to geodynamic principles103; a method potentially applicable to any time period for which continuously closing plate topologies exist. For discussion on how GPlates implements absolute reference frames see Suppl. Material.

Glossary terms

Alkalic magmatism: magmas that are distinguished by a high alkali metal oxide composition (K_2O, Na_2O) relative to silica, reflect low degrees of partial melting of their source region and are commonly found in continental rifts.

Apparent Polar Wander Path (APWP): the apparent motion of the magnetic axis through time, as perceived from a temporal sequence of paleomagnetic poles derived from a stationary point of reference (e.g. a continent at present-day).

Continuously closing plate topologies: a method of creating a network of plate boundaries that combine to define a tectonic plate whose shape and size changes through time.

Diffuse deformation: areas where internal plate deformation is distributed over wide lateral areas rather than narrowly localised at a rigid plate boundary.

Earth System Models (ESM): global models that integrate processes occurring in the biosphere, hydrosphere and lithosphere.

Euler pole: point on a sphere defining an axis of rotation (arbitrarily as one end of an axis passing through the centre of the sphere), about which the motion of a plate can be described.

Fracture zone: linear feature on the present-day seafloor which traces the direction of seafloor spreading at paleo-mid-ocean ridges.

Geocentric axial dipole (GAD) hypothesis: on timescales of 105-106 years, the Earth's magnetic field can be approximated by a magnetic dipole that is centred at Earth's centre and aligned parallel to the planetary spin-axis.

Geomagnetic polarity timescale: geological timescale linking the sequence of reversals of the geomagnetic field to geochronology and stratigraphy.

Kimberlites: ultramafic igneous rocks that are the main host rocks for diamonds,, and whose eruption sites have been linked to the edges of the LLSVPs.

Large Igneous Provinces: a large volume of igneous rock emplaced over a geologically short period; commonly ascribed to the first arrival of a mantle plume (the plume 'head') to Earth's surface.

Large Low Shear Velocity Provinces: lowermost mantle structures of uncertain physical nature, defined by the robust observation that shear waves (and also P-waves) propagate markedly slower inside the province than in ambient mantle. LLSVPs are thought to represent the deep source regions of mantle plumes.

Low-temperature thermochronology: application of radiometric dating to determine the time at which a mineral cooled below a 'closure temperature' (which is method-specific, but generally in the range ~70-400 degrees C), below which the radiogenic daughter products are retained.

Magnetic anomaly identifications: also commonly known as a magnetic anomaly pick is a spatio-temporal representation of a marine magnetic anomaly that has been interpreted based on a synthetic crustal magnetic model and the geomagnetic polarity timescale.

Volcanic hotspots: volcanism (commonly intraplate) with distinct geochemical signatures, thought to be caused by a mantle plume, but with a much lower eruptive rate than a LIP.

Mantle plume: an upwelling of buoyant, hot mantle rock from the mantle, hypothesised to be the causative mechanism of Large Igneous Provinces and time-progressive volcanic hotspot tracks.

Oceanic gateways: narrow, shallow, diffuse connections between neighbouring oceans, which facilitate the large-scale exchange of water, heat, salinity and nutrients between ocean basins.

Orogenic belt: zone of collision along convergent plate margins, resulting in the formation of a mountain range.

Palaeomagnetic pole: the apparent position of the magnetic pole at some time in the past, relative to some fixed point of reference (e.g. a continent at present-day); determined from palaeomagnetic records.

Passive margin: is a non-active plate margin composed of stretched continental crust that was once the site of continental extension, which ultimately gave way to seafloor spreading.

Plume Generation Zone (PGZ): marginal areas of the LLSVPs in the lowermost mantle, associated with strong lateral gradients in seismic wave velocities.. Such LLSVP edges have been proposed as the nucleation sites of mantle plumes.

Radiometric dating: a method to estimate the numerical age of igneous and metamorphic rocks, by measuring the decay products of radioactive isotopes in the rocks'constituent minerals .

Seafloor spreading isochrons: lines of equal age drawn on the seafloor depicting the seafloor spreading record, and theoretically representing palaeo-mid-ocean ridge locations.

Seamount: a topographically isolated submarine feature that rises from the seafloor, typically formed by volcanic activity.

Seismic tomography: a geophysical technique that renders 2D or 3D images of the Earth's interior structure (i.e., the spatial distribution of properties such as seismic velocity, anisotropy, attenuation, density) by analysing recordings of seismic waves that traversed the interior.

Small circles: a circle formed on the surface of a sphere by the intersection of a plane that does not pass through the centre of the sphere.

Stage rotation: rotation about an Euler pole that describes the motion of a plate between two specific times.

Supercontinent: The aggregation of most continental crust into a single landmass.

Syn-rift sedimentary sequences: sedimentary rocks deposited during continental rifting that are characterised by coarse grained,poorly sorted terrestrial deposits.

Tectonic plate: a rigid body of crust and uppermost mantle, delimited against other plates by tectonically active boundaries such as subduction zones, mid-ocean ridges and transform faults.

True Polar Wander (TPW): a rotation of the entire solid Earth (crust and mantle together) in response to mass re-distributions that perturb the planetary moment of inertia. TPW acts to restore the principal moment of inertia to the planetary spin-axis, and so TPW rotations always occur about an equatorial axis.

Volcanic arc: linear, trench-parallel belt of volcanoes that develops about 80-100 km above a subducting slab. Represents a key marker of convergent plate margins.

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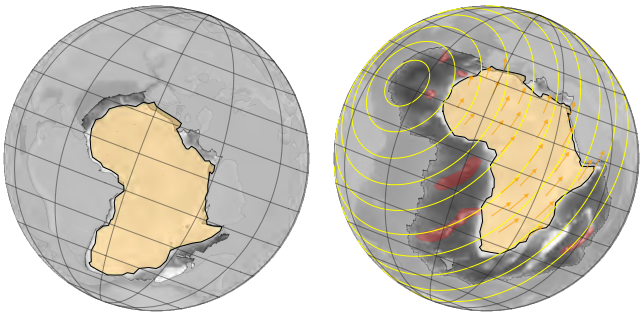
Basic Concepts for Describing Plate Motions

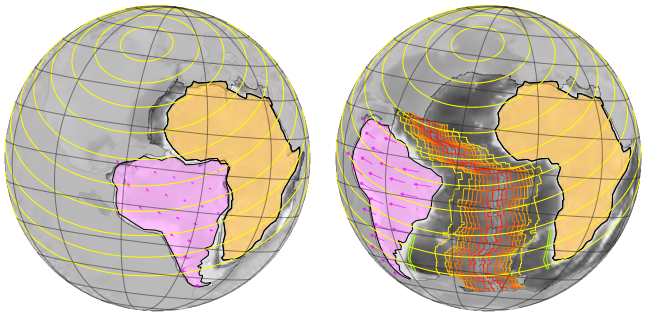
Absolute Plate Motion

(e.g. Motion of Africa recorded by Hotspot Trails)



Relative Plate Motion

(e.g. South Atlantic opening recorded by seafloor)



Methods for Reconstructing Absolute Plate Motions

Polar Wander from paleomagnetism

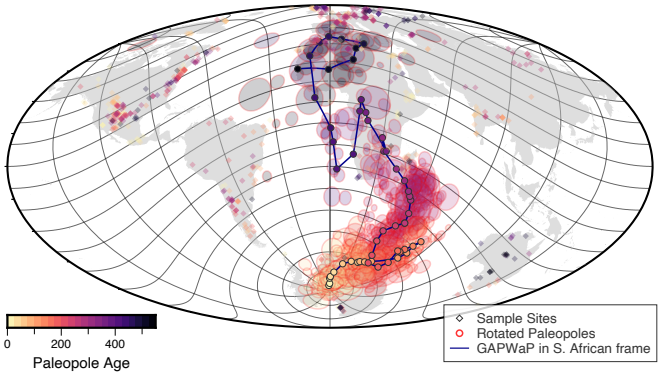
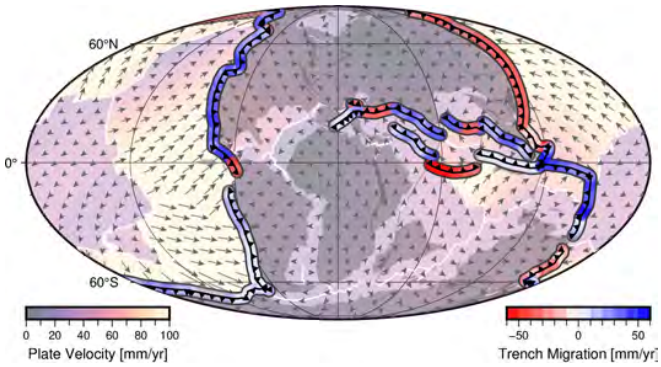
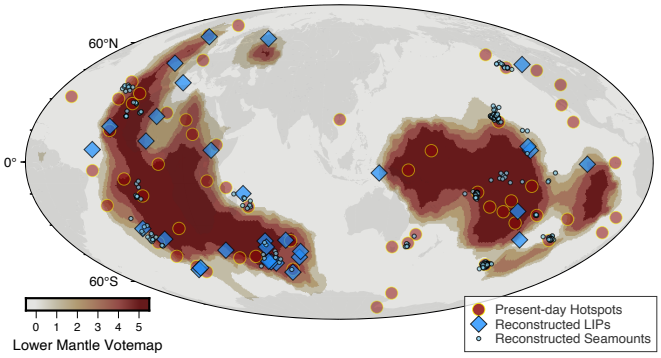


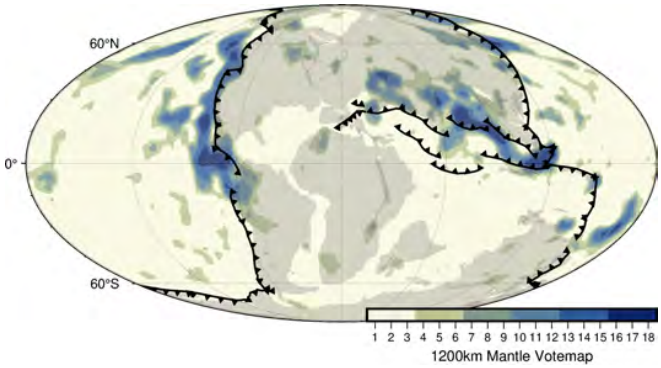
Plate Kinematic Optimization

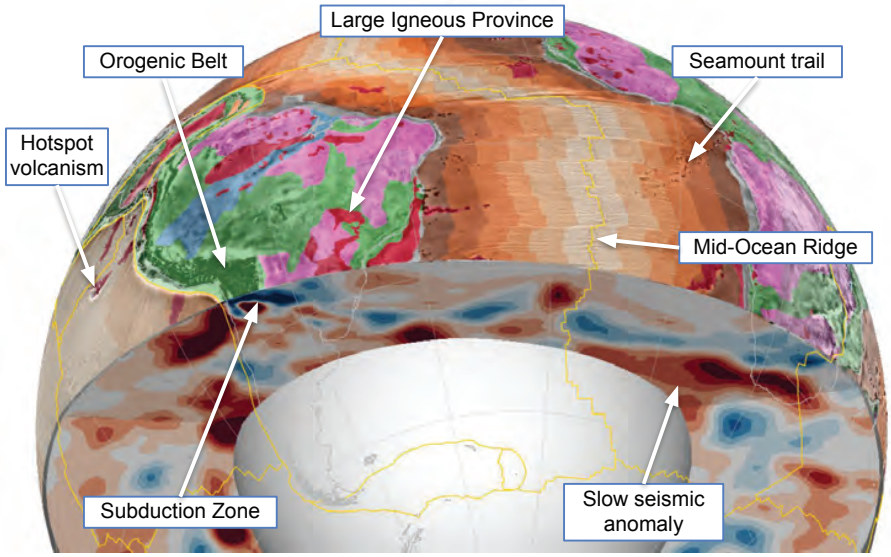


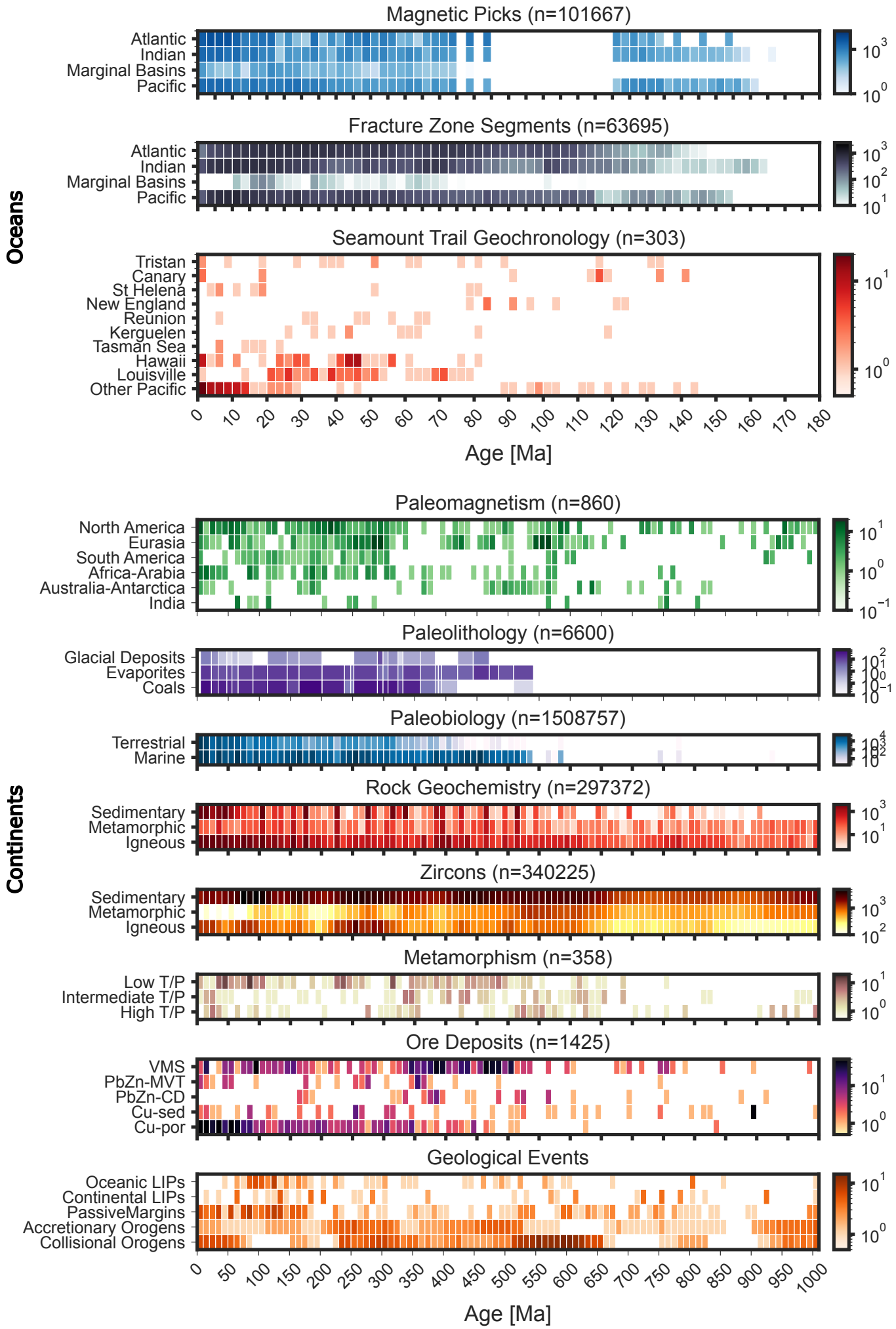
Plumes and Surface Volcanism

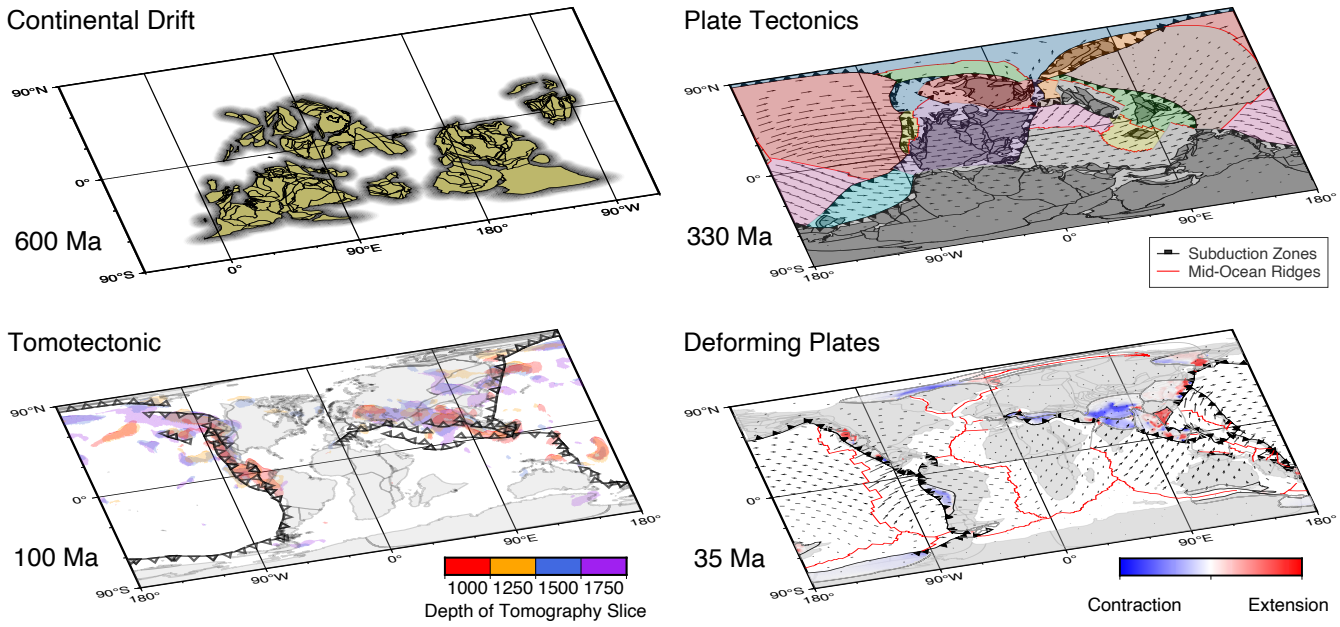


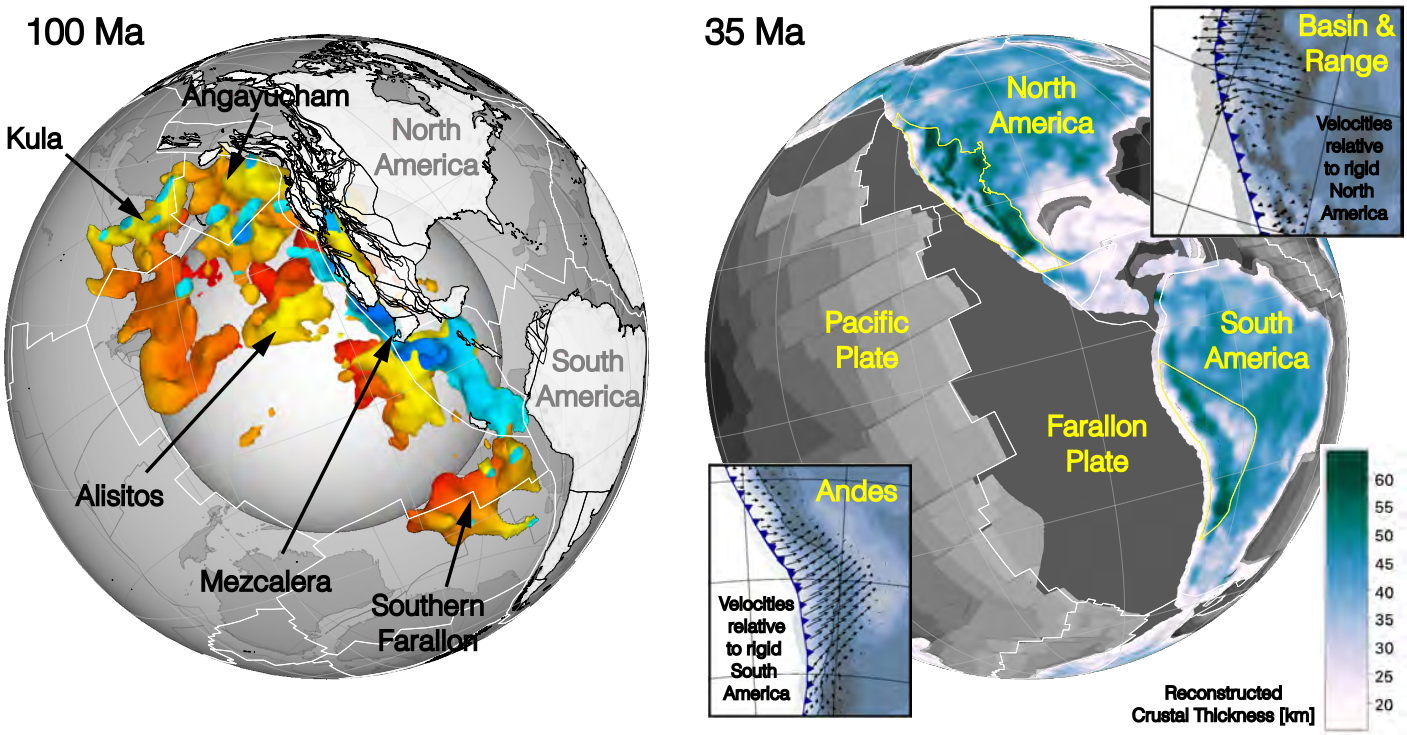
Slab-remnant mapping

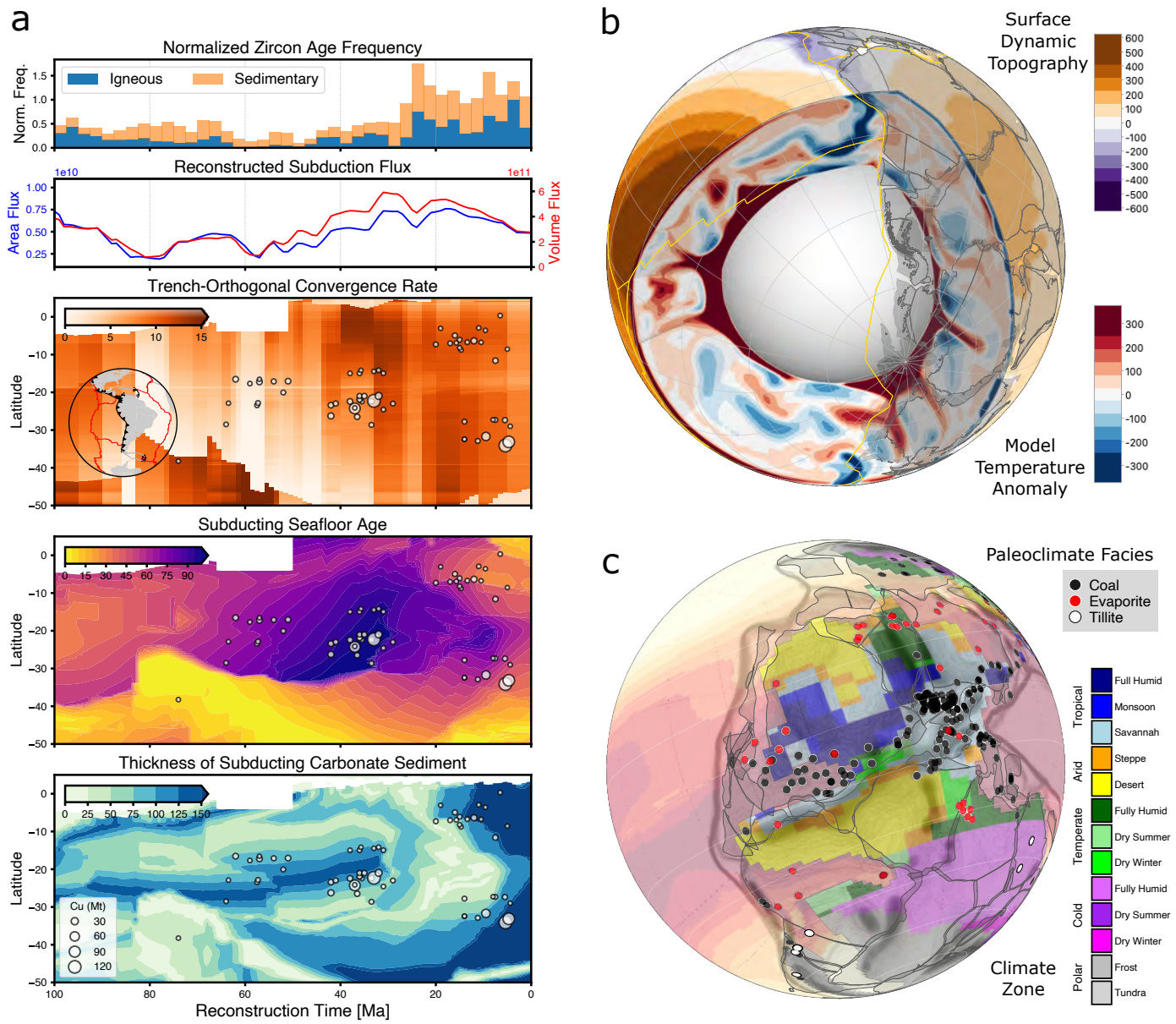


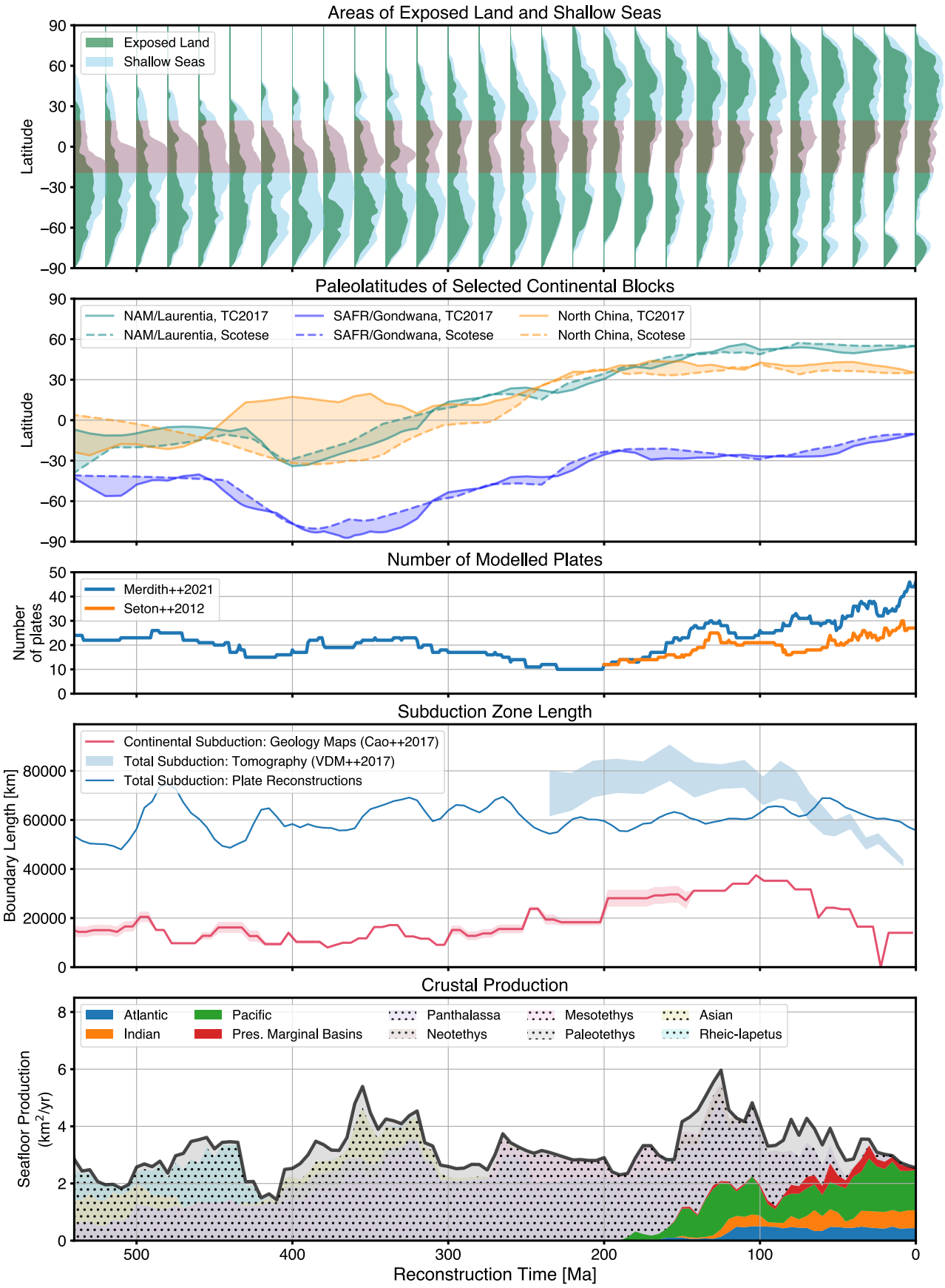

Large Igneous Province
Orogenic Belt
Seamount trail
Hotspot volcanism
Mid-Ocean Ridge
Subduction Zone
Slow seismic anomaly


Oceans
Magnetic Picks (n=101667)
Atlantic
Indian
Marginal Basins
Pacific
Fracture Zone Segments (n=63695)
Atlantic
Indian
Marginal Basins
Pacific
Seamount Trail Geochronology (n=303)
Tristan
Canary
St Helena
New England
Reunion
Kerguelen
Tasman Sea
Hawaii
Louisville
Other Pacific
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180
Age [Ma]
Continents
Paleomagnetism (n=860)
North America
Eurasia
South America
Africa-Arabia
Australia-Antarctica
India
Paleolithology (n=6600)
Glacial Deposits
Evaporites
Coals
Paleobiology (n=1508757)
Terrestrial
Marine
Rock Geochemistry (n=297372)
Sedimentary
Metamorphic
Igneous
Zircons (n=340225)
Sedimentary
Metamorphic
Igneous
Metamorphism (n=358)
Low T/P
Intermediate T/P
High T/P
Ore Deposits (n=1425)
VMS
PbZn-MVT
PbZn-CD
Cu-sed
Cu-por
Geological Events
Oceanic LIPs
Continental LIPs
PassiveMargins
Accretionary Orogens
Collisional Orogens
0 50 100 150 200 250 300 350 400 450 500 550 600 650 700 750 800 850 900 950 1000
Age [Ma]


Continental Drift
600 Ma
90°N
0°
90°S
0°
90°E
180°
90°W
Plate Tectonics
330 Ma
Subduction Zones
Mid-Ocean Ridges
Tomotectonic
100 Ma
1000 1250 1500 1750
Depth of Tomography Slice
Deforming Plates
35 Ma
Contraction
Extension


100 Ma
Kula
Angayucham
North America
South America
Alisitos
Mezcalera
Southern Farallon
35 Ma
North America
Basin & Range
Velocities relative to rigid North America
Pacific Plate
South America
Farallon Plate
Andes
Velocities relative to rigid South America
60
55
50
45
40
35
30
25
20
Reconstructed Crustal Thickness [km]


a
Normalized Zircon Age Frequency
Norm. Freq.
Igneous
Sedimentary
Reconstructed Subduction Flux
Area Flux
Volume Flux
1e10
1e11
Trench-Orthogonal Convergence Rate
Latitude
Subducting Seafloor Age
Thickness of Subducting Carbonate Sediment
Cu (Mt)
Reconstruction Time [Ma]
b
Surface Dynamic Topography
Model Temperature Anomaly
c
Paleoclimate Facies
Coal
Evaporite
Tillite
Climate Zone
Tropical
Arid
Temperate
Cold
Polar
Full Humid
Monsoon
Savannah
Steppe
Desert
Fully Humid
Dry Summer
Dry Winter
Fully Humid
Dry Summer
Dry Winter
Frost
Tundra


Areas of Exposed Land and Shallow Seas
Exposed Land
Shallow Seas
Latitude
90
60
30
0
−30
−60
−90
Paleolatitudes of Selected Continental Blocks
NAM/Laurentia, TC2017
NAM/Laurentia, Scotese
SAFR/Gondwana, TC2017
SAFR/Gondwana, Scotese
North China, TC2017
North China, Scotese
Latitude
Number of Modelled Plates
Merdith++2021
Seton++2012
Number of plates
50
40
30
20
10
0
Subduction Zone Length
Continental Subduction: Geology Maps (Cao++2017)
Total Subduction: Tomography (VDM++2017)
Total Subduction: Plate Reconstructions
Boundary Length [km]
80000
60000
40000
20000
0
Crustal Production
Atlantic
Indian
Pacific
Pres. Marginal Basins
Panthalassa
Neotethys
Mesotethys
Paleotethys
Asian
Rheic-Iapetus
Seafloor Production (km²/yr)
8
6
4
2
0
500
400
300
200
100
0
Reconstruction Time [Ma]