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Overview on GPlates: focus on plate reconstruction

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Abstract: Plate tectonic reconstructions have been employed in geosciences since 1970s, in the context of hydrocarbon exploration, regional geology and paleobiology. Such studies have given valuable inputs for climate and geodynamic computations, present-day mantle structure, models of plate motion, and the interpretation of the drift of hotspots, true polar wander (TPW), sea level and stratigraphic signals. However, geodynamic models generated in the past by incorporating global plate tectonic reconstructions have limitations. To overcome this, GPlates software brings forward a new era of interactive plate tectonic reconstruction software integrated with GIS databases that incorporates a wide variety of geological and geophysical data. Besides modelling tectonic and crustal evolution, GPlates has also been used in visualizing paleogeography and paleobathymetry, in understanding deep carbon cycle, subduction zone initiation, mantle evolution, investigating earthquakes and predicting future supercontinents. the software has been widely used in hydrocarbon exploration along the passive conjugate margins such as from the margins of South America and Africa and has provided promising results in acquiring new and more reliable prospecting criteria for petroleum systems. Additionally, it has become an integral tool for paleolatitude calculations, modelling of paleoclimate and paleoenvironment. This article reviews key plate reconstructions that have been carried out using GPlates, the typical constraints and the set of input parameters.

Key words: Simulation, geodynamics, deformation mechanism

1. Introduction

GPlates, an open-source software, is an interactive and user-friendly tool for visualizing and modifying plate tectonic reconstruction. This is achieved by incorporating high-resolution geological and geophysical data with reference to the geological time scale into the GPlates. The software permits the user to import a diverse range of datasets to analyse the spatial and temporal relationships of the deforming plates and the relative motion between rigid plates (Williams et al., 2012). GPlates functions as a 'plate tectonic geographic information system (GIS)' where the constraints of reconstruction can be fixed and the tectonics can be visualized with reference to the dynamic nature of the mantle convection. The software is supported by GPML (GPlates Markup Language) and allows the visualization of raster and vector data that can be geological, geophysical, and paleogeographical data in a plate tectonic context. The software is also equipped to visualize the 3D scalar fields of the subsurface and link the mantle convection models with tectonic models.

GPlates was developed in 2006 by the EarthByte Group in the school of Geosciences at the University of Sydney (Australia) and the Division of Geological and Planetary Sciences (GPS) at Caltech (USA). Since its advent, GPlates has been used extensively to visualize plate reconstructions, study the surface tectonic processes as a function of the mantle convection models, and as a piece of supporting evidence in paleogeography and paleoclimate studies.

This article gives an overview of (i) plate reconstructions carried out using GPlates, (ii) the typical parameters used to do so, and (iii) the most ubiquitous applications of GPlates.

2. Overview on plate reconstruction methodology

Plate reconstruction is the process of restoring the positions of tectonic plates relative to each other, spatially and temporally, by restoring the plates into their positions occupied in the geologic past. It is carried out by studying the plate motions relative to a reference frame, e.g., the Earth's magnetic field or the hotspot trails. The position and motion of plates in the geologic past can be estimated using several parameters: geometric fit of the plates, continent ocean boundaries, seismic data, gravity anomalies, paleomagnetic data, bathymetry, hotspot trails, orogenic belts and rock provinces (Engen et al., 2000). The classical approach towards reconstruction has been described by Pitman and Talwani (1972), where the data from (i) positions of both present and extinct spreading

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axes, (ii) positions and identities of magnetic sea-floor spreading anomalies, (iii) positions and azimuths of fracture zones, and (iv) the continent-ocean boundary have been used to find the instantaneous rotation poles of the plates.

GPlates is not the first and only platform for dealing with paleomagnetic data and visualizing plate reconstructions. Machintosh developed PaleoMac in 2003, but that is supported only on macOS. However, GPlates has evolved into a more accessible and versatile platform than any of its counterparts. GPlates is freely available on Windows, Linux, and macOS and comes with its own python library pyGPlates (https://www.gplates.org/docs/pygplates/). The software offers access to extensive data and models (Table 1) that are continuously updated and developed. Interpolatibility with GIS software and seismic data, and usability with other methods such as seismic tomography and numerical modelling gives GPlates an edge over its contemporaries. It can be simultaneously used with other software e.g., CitcomS, IAPD, GoogleEarth and GMT, and has been applied to various fields of geosciences; in mantle modelling, computing paleo-coordinates, investigation of earthquakes and in predicting future supercontinents.

3. Commonly used parameters in GPlates

GPlates supports a number of vector and raster data that are applied to develop plate reconstruction models. Table 2 presents a list of the available geological and geophysical data commonly employed to calculate the relative motion of blocks. This section takes up a few of them and gives an extensive overview of case studies.

3.1. Paleomagnetic data

Since the Mesozoic Period onward, paleomagnetism is the only source of quantitative information available that gives an idea about the position of plates since hotspot motions, *in-situ* oceanic crust and seismic imagery of that time-span are unavailable. The study of paleomagnetism gives the paleolatitude of the cratonic blocks and their movement history with respect to the Earth's spin axis. Using this dataset, continental blocks whose relative motions influenced each other are grouped into clusters of localized hierarchies (Figure 1). In Figure 1a, the history of motion of a plate is described relative to another plate, and the African plate is usually located at the top of the tree like hierarchy. In Figure 1b, for the pre-Mesozoic era, absolute motions of the plates are considered, and a flat hierarchy is maintained. Figure 1c presents a hybrid type hierarchy where there are two groups within which the plates are related in a tree like hierarchy and the clusters are related by their absolute plate motions. High-quality paleomagnetic data, usually found for the Phanerozoic, have been used to construct the apparent polar wander path (APWP), and eventually a continental drift framework is created (Merdith et al., 2012b).

Merdith et al. (2021b) compiled several plate models to present a global plate tectonic model that spans over 1 Ga and includes the Neoproterozoic and the Phanerozoic. Paleomagnetic data and geological constraints were used and those explain the passive margins for divergence and magmatic arcs for convergence. On the other hand, paleomagnetic data gives an absolute quantitative value of constraints for the movement of plates. This model uses several clusters of cratonic components. These clusters are usually separated by the presence of a large ocean basin. High-quality paleomagnetic data, usually since the Phanerozoic, are used to construct the APWP, and ultimately, a continental drift framework is created. The geologic data is then introduced in the form of plate boundaries and incorporated into the model so that it becomes compatible with both the paleomagnetic and geological constraints. The constraints are mainly structural and metamorphic and are primarily employed to infer the subduction polarity, collision period and rift orientations.

Westerweel et al. (2019) studied the collision between the Asian and the Indian plates and presented a tectonic history of the modern Burma/Myanmar terrane by adopting the global rotations and polygons from the GPlates model of Matthews et al. (2016b). The paleogeography of India and Asia at 60 Ma was reconstructed (Figure 2), using the paleomagnetic data from the Mayanmar terrane and the seafloor magnetic isochrones on the present-day oceanic crust. The reconstructions were done using the Matthews GPlates model's combined hotspot (0–70 Ma) and paleomagnetic (70–250 Ma) reference frames.

Oriolo et al. (2021) compiled a set of ecologic, paleomagnetic, petrologic, geochronologic and isotopic data to put forward an evolutionary model of the accretionary orogens in the western margin of Gondwana throughout the Paleozoic. GPlates was used to reconstruct the paleogeography of the western Gondwana at 540 Ma (Figure 3), based on the paleomagnetic database of Scotese (2016).

Li and Evans (2011) proposed a model for the Neoproterozoic evolution of the Australian cratons that resolved the long-standing paleomagnetic discrepancies within the Australian craton using the GPlates software.

This model affects the reconstruction of Rodinia by altering the APWP of Australia and resolves the contradictory views on the age of breakup of Rodinia given by the paleomagnetic and stratigraphic analyses.

The Parnaiba basin, once a part of Gondwana, was studied by Jaju et al. (2018) to reconstruct the evolution of paleoclimate and paleogeography during the Permian-

Triassic using GPlates. The paleomagnetic frame of reference (van Hinsbergen et al., 2015) was used to link the northwards drift and rotation of the South American plate

Table 1. Datasets of GPlates supported models, https://www.earthbyte.org/category/resources/data-models/global-regional-plate-motion-models/ (Accessed on 20 November 2021).

Sl. no.	Author(s)	Time range Ma)	Data set
1	Merdith et al. (2021a)	1000–0	Combined the previous Neoproterozoic and the Phanerozoic models and proposed
2	Clennett et al. (2020)	170–0	Plate Reconstruction of North America and the Pacific Basin
3	Müller et al. (2019)	250–0	Global Plate Model Since the Triassic incorporating deformation along the plate boundaries
4	Young et al. (2019)	410–0	Modelling tectonic plates and subduction zones since the late Paleozoic Era
5	Merdith et al. (2017)	1000–520	Plate reconstruction of the Neoproterozoic Period
6	Matthews et al. (2016a)	410–0	Kinematic evolution of the global plate boundaries since the Paleozoic Era
7	Zahirovic et al. (2016)	230–0	Evolution of the Tethys since Jurassic
8	Müller et al. (2016)	230–0	Post-Pangea events of plate reorganisations and evolution of ocean basins
9	Scotese (2016)	1100–0	PaleoAtlas for GPlates, PaleoData Plotter Program, PALEOMAP Project
10	Zahirovic et al. (2014)	200–0	Tectonic evolution of Southeast Asia since Cretaceous
11	Shephard et al. (2013)	200–0	Tectonic evolution of the Arctic by integrating geology and geophysics with mantle structure
12	Seton et al. (2012)	200–0	Global reconstruction of continental and ocean basin since 200 Ma
13	Shephard et al. (2012)	140–0	Study of geodynamic mantle heterogeneity structure in relation to absolute plate movements
14	Gumis et al. (2012)	140–0	Plate Tectonic Reconstructions involving rigid plates
15	Li et al. (2008)	1100–530	Tectonic history of Rodinia

Table 2. Common parameters used for plate reconstruction used in GPlates

Raster data	Vector data (Features)
•Bouguer anomalies	•Coastlines
•Crustal strain	•Continent Ocean Boundaries
•Crustal thickness	•Flowlines
•Free air gravity anomalies	•Gridmarks
•Isostatic gravity anomalies	•Isochrons
•Magnetic anomalies	•Hotspots
•Seafloor age	•Large igneous provinces
•Topography	•Paleomagnetic data
•Vertical gravity	•Rotations
	•Seafloor
	•Extinct and present ridges

(Paleozoic) with the mineralogical, organic and inorganic geochemical, and the tectonostratigraphic evidence from the intracratonic Parnaiba Basin. It was observed that the paleogeographic reconstruction by GPlates was generally comparable to the climate model, the plate motion model, lithostratigraphic record, and the chemostratigraphic data.

In the Famatian orogen, Guena et al. (2021) studied the paleomagnetism of the hematite from the El Hongo trondhjemite. The paleomagnetic studies gave two possible suggestions: (i) a clockwise rotation, and (ii) the other resembles the APW path of Gondwana in the Early Paleozoic. Plate reconstruction of the Río de la Plata craton and the Pampia block was done using GPlates by Geuna et al. (2021) (Figure 4).

Besides geologic constraints, paleomagnetic data has also been used in association with other plate reconstruction tools such as seismic data. Clennett et al. (2020) provide a detailed tectonic history of the Pacific since 170 Ma by incorporating seismic tomography, hotspot trails and paleomagnetic frame of references. The location of the subducted lithosphere in the mantle refers to the extinct subduction zones, which furnish a reference to deduce the plate motions.

3.2. Seismic data

Vormann and Jokat (2021) compiled the magnetic and seismic data of five seismic profiles along the east African coast and performed kinematic reconstruction using GPlates to fit the Davie ridge between the African coastline and the southern Madagascar.

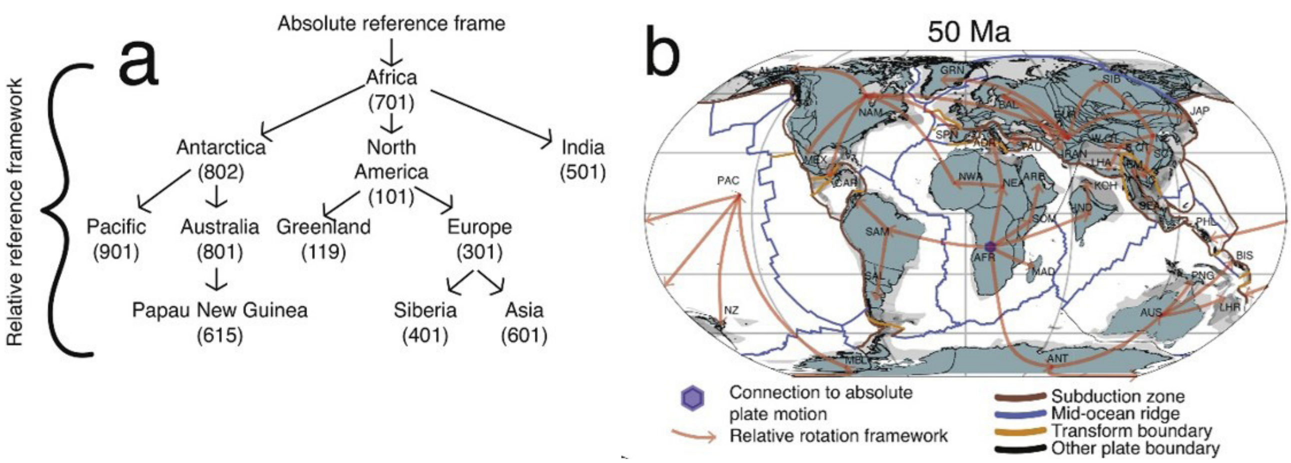

Figure 1. (a) Schematic of a tree like hierarchy and its simplified map view. Reproduced from figure 2 of Merdith et al. (2021b).

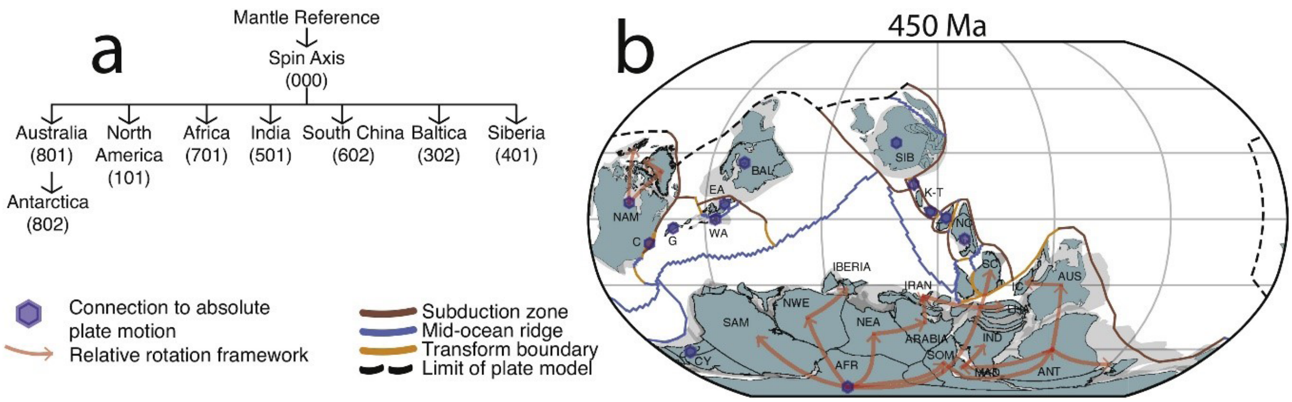

Figure 1. (b) Schematic of a flat hierarchy and its simplified map view. Reproduced from figure 3 of Merdith et al. (2021b).

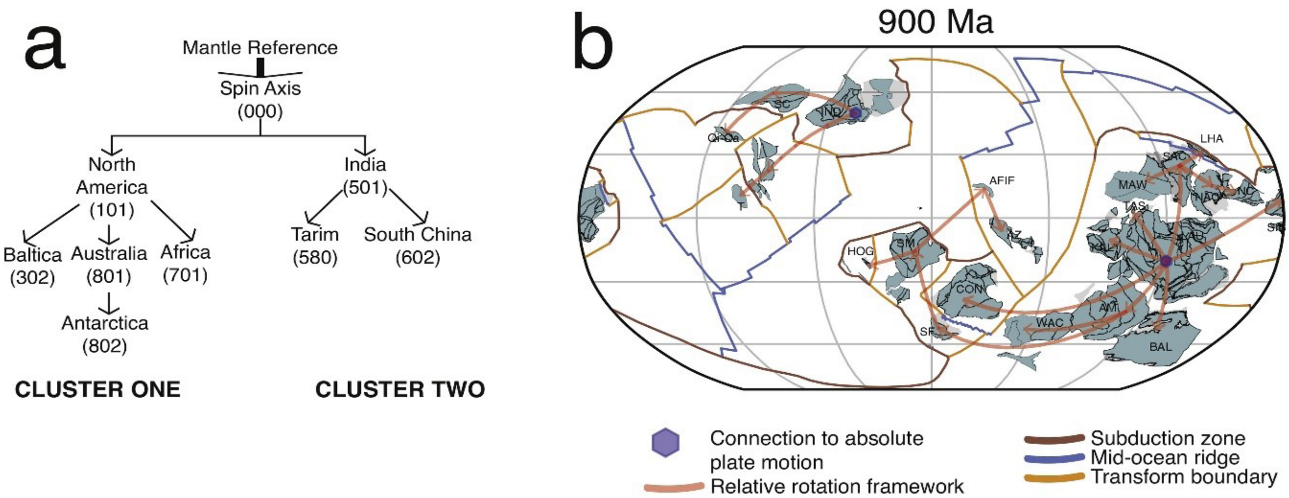

Figure 1. (c) Schematic of a hybrid plate motion hierarchy and its simplified map view. Reproduced from figure 5 of Merdith et al. (2021b).

Tomasi et al. (2021) presented additional constraints on the Gondwana breakup by restoring the magma-rich rift margins. The methodologies of rift domain mapping from seismic reflection interpretation, and crustal thickness mapping (using gravity inversion and lithosphere thinning from subsidence analysis) were used to create a three-

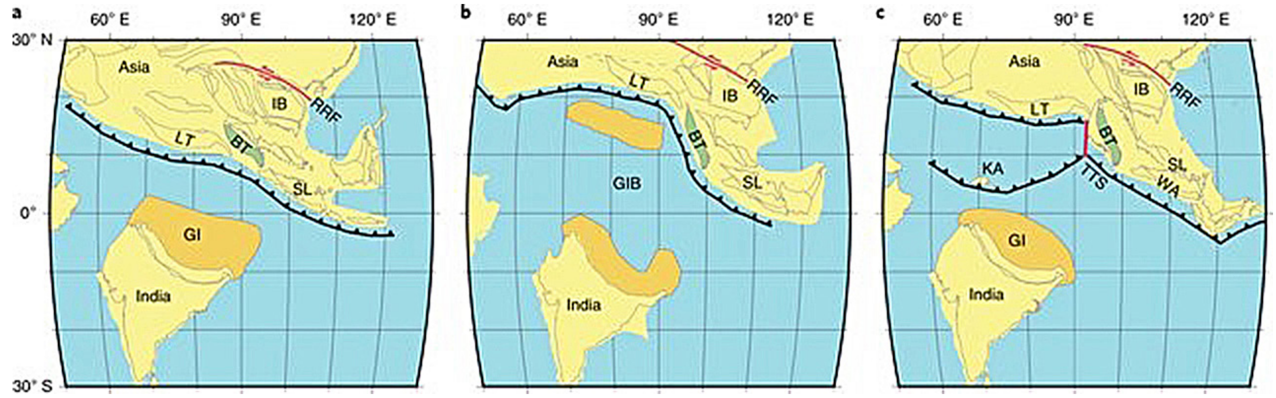

Figure 2. Alternative plate reconstructions of India-Asia paleogeography at 60 Ma. Reproduced from figure 1 of Westerweel et al. (2019).

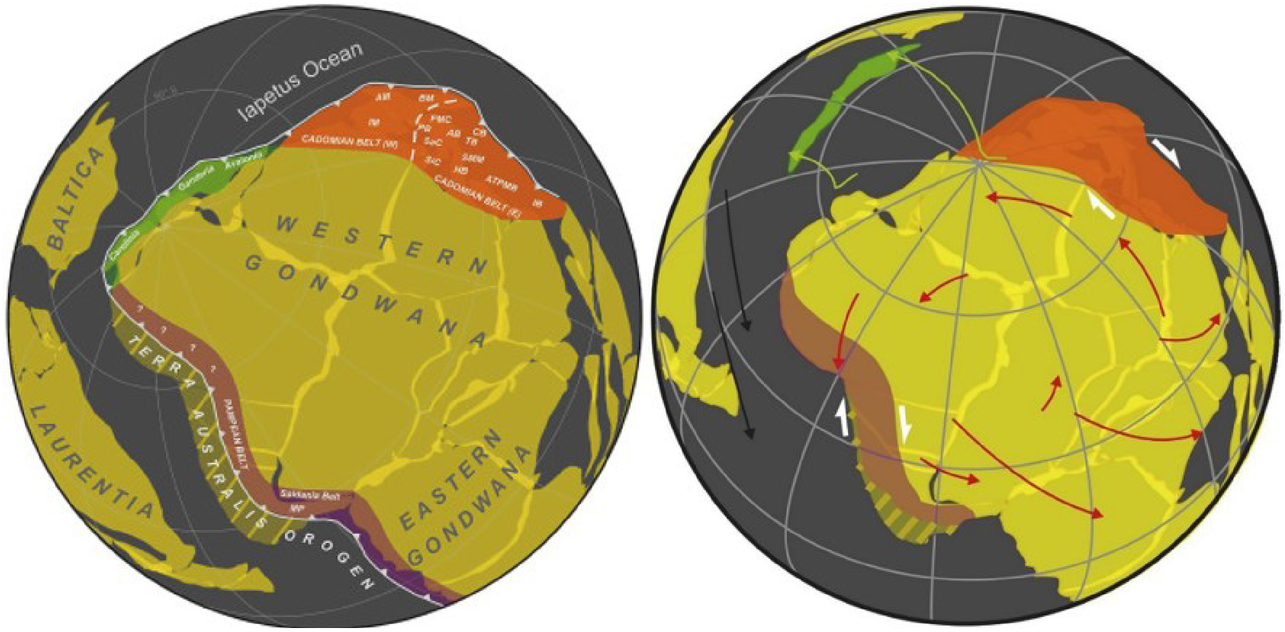

Figure 3. Paleogeographic reconstruction of the western Gondwana at 540 Ma (left) and Late Cambrian-Early Ordovician displacement vectors (right). Reproduced from figure 1 of Oriolo et al. (2021).

phase tectonic evolutionary model of the Mozambique-Antarctica margins.

An evolutionary model of the multiple rifting episodes in the Irish Atlantic margin is put forward by Yang and Welford (2021), using new data from seismic profiles and field data. GPlates is used to restore the plates across the Porcupine Atlantic-Flemish Cap margins using the crustal domain map and bathymetric contour data (Figure 5) following the principle of reconstruction of rigid plates.

3.3. Magnetic and gravity anomalies

GPlates has extensively been used in the tectonic study and reconstruction of the Australian craton and its constituent blocks. Williams et al. (2012) studied the Proterozoic evolution of the Australian craton and the relative movement between the northwest and the south Australian cratons, by incorporating the model of Li and Evans (2011) and the magnetic anomaly map of Australia. They compared the different proposed models to find the best fit.

Gibbons et al. (2012a) presented a regional model of the tectonic features of the western Australian margin, including volcanic ridges, submerges plateaus, fracture zones, and put forward a connection between the Jurassic and Cretaceous rifting events. The model incorporates free-air gravity anomalies, revised seafloor spreading magnetic anomalies, deformation constraints of fracture zones, extinct ridges, oceanic plateaus, and the crustal age data from the West Australian abyssal plain to resolve the discrepancy of the Jurassic extent of the Greater India.

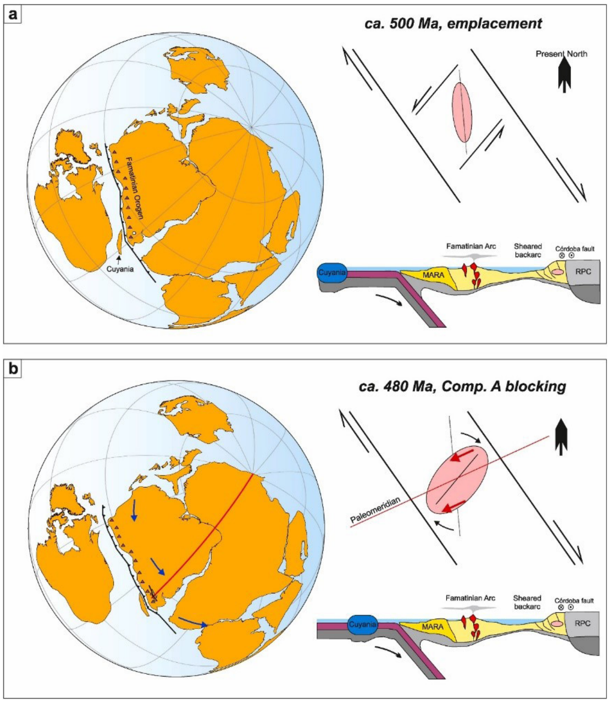

Figure 4. Paleomagnetic reconstructions at 500 Ma and 480 Ma respectively; blue arrows show displacement vectors for Gondwana relative to the Laurentia. Reproduced from figure 15 of Geuna et al. (2021).

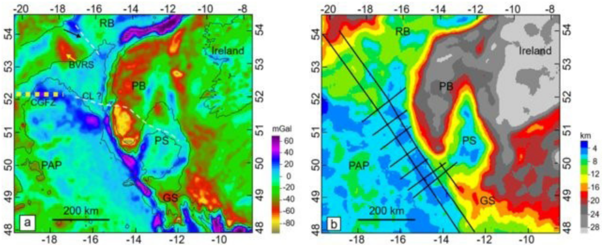

Figure 5. Map of free air gravity anomaly with overlying bathymetric contours (left); Crustal thickness derived from gravity inversion (right). Reproduced from figure 5 of Yang and Welford (2021).

Dumais et al. (2021) described the evolutionary history of the region around the Knipovich Ridge in the Arctic using magnetic anomalies and aeromagnetic data. The GPlates reconstruction was done using the available plate boundary and magnetic isochron data along two profiles across the Knipovich Ridge.

Tominaga and Hara (2021) used GPlates to reconstruct the paleogeography of the Mikabu plateau, based on the movement of the Izanagi plate, by following Müller et al.'s (2016) reconstruction using magnetic isochrones and hotspot tracks over the Pacific. Additional constraints were superposed with this reconstruction, namely, the eruption age of igneous rocks in the Mikabu Unit (157 Ma), accretion ages of the Kashiwagi (130–120 Ma) and Kamiyoshida units (170–160 Ma), and the minimum accretionary age of the Mikabu Unit of 110 Ma (Figure 6).

Ratheesh Kumar et al. (2020) studied the deformation constraints of the link between India and Sri Lanka using the parameters of crustal thickness and elastic thickness following a flexure inversion model. GPlates was used to build paleo-fit based reconstruction models by using the previously published magnetic anomaly data.

A kinematic model for Iberia has been presented by Angrand et al. (2009), which incorporates the possible connections between the Atlantic and Neotethyan regions, and includes constraints from 270–100 Ma. A number of previously published kinematic models were implemented, e.g., reconstruction of the North Atlantic based on magnetic anomalies, along with the models for Africa, North America-Europe and the Mediterranean. These models were updated by using certain deformation constraints.

Dallanave et al. (2020) studied the magnetostratigraphic data from the New Caledonian region and combined it with that from the region around New Zealand to determine the age of the sedimentary rocks, and consequently they present a model of the tectonic activity of the region and onset of a new plate during the Eocene. The GPlates reconstruction used previously published the rotation values and poles, and fixed the Pacific plate as the anchored plate.

3.4. Deformation constraints

Gion et al. (2017) presented a model of the crustal deformation during the Paleogene Eurekan orogeny, based on the modified version of the model proposed by Shephard et al. (2013) using the GPlates software, as a base model to study the evolution of the related basins. Several published geological and geophysical datasets, along with the rotation poles from previous studies and deformation constraints (strike-slip motions, shortening amount), were used to generate this model (Figure 7).

Riefstahl et al. (2020) studied the region of Chatham Rise and the initiation of breakup between Zealandia and Antarctic, using seismic data along three profiles (wide-angle seismic reflection/refraction, multichannel seismic and potential field data) across the Southern Chatham Rise margin and the SE Chatham terrace. Plate reconstruction was carried out using GPlates, and the rotation parameters were taken from multiple sources.

Turco et al. (2021) used deformable plate kinematics approaches to describe the opening of back-arc basins and the formation of associated accretionary wedges, as observed in the central Mediterranean region, during the formation of Apennine chain and the Tyrrhenian basin.

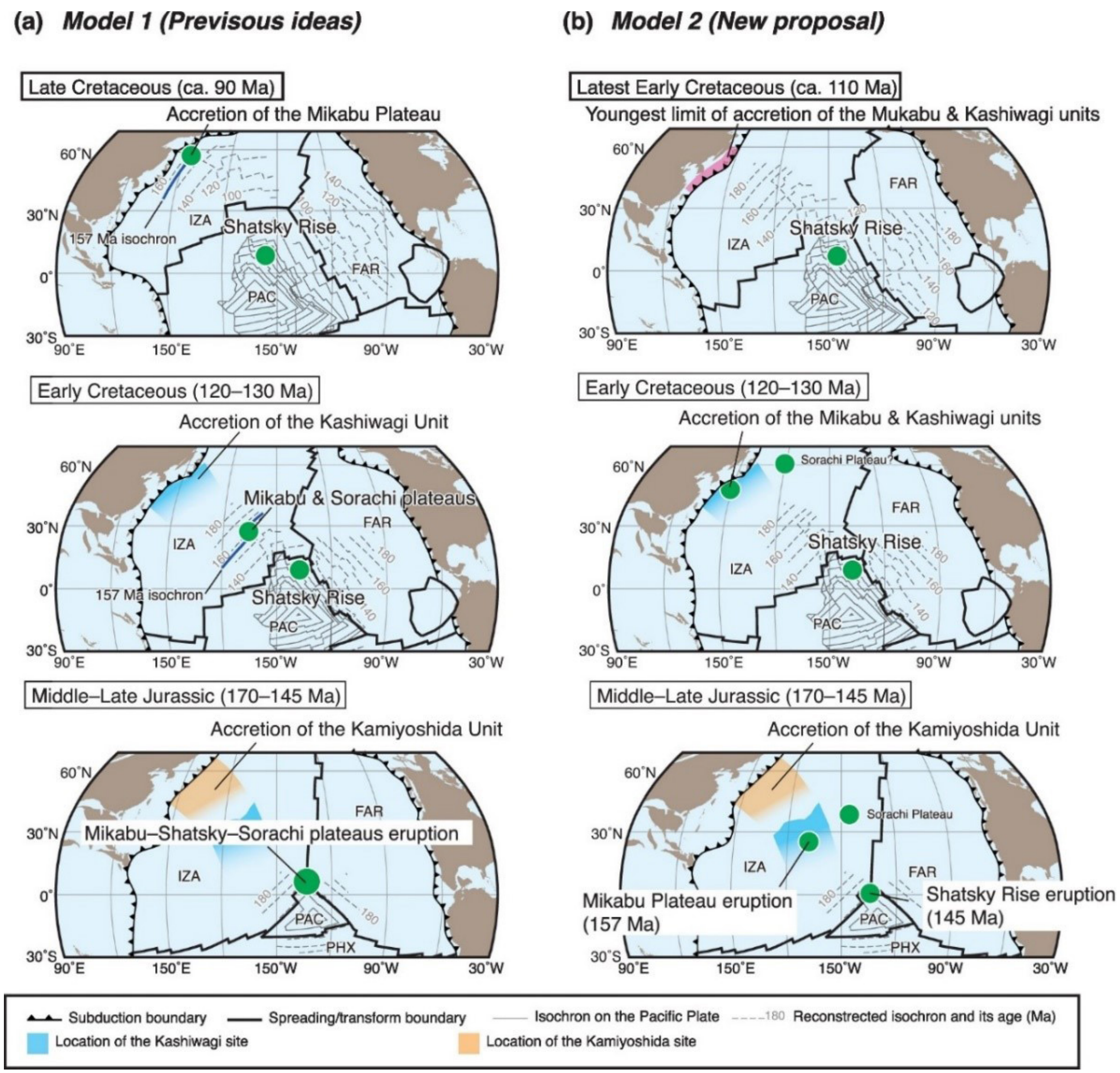

Figure 6. Paleogeographic maps showing the development of the oceanic plate in the paleo-Pacific ocean. Reproduced from figure 10 of Tominaga and Hara (2021).

The lineaments and the extensional structures of the region coincide with the boundaries of the polygons that are in accordance with their Euler pole grids constructed using GPlates. The angle of rotation and the angular velocity of these blocks were determined using the methods of crustal balancing and stratigraphic records, respectively.

3.5. Coastlines and previously published tectonic models

Coastlines and geometric fit of continents are commonly used as parameters for plate tectonic reconstruction. Schoettle-Greene et al. (2020) used GPlates to reconstruct the position of the Yakutat terrane from 25 Ma in 5 Ma increments based on the previously published kinematic models. A review on the evolution of the Patagonian basins from Paleozoic to Triassic has been presented by Suarez et al. (2019), where the paleogeographic reconstruction of Patagonia at 200 Ma has been done using the coastlines data given by Seton et al. (2012) and modified to fit Antarctica based on the model of Lawver et al. (1998). Scotese (2021) used the PaleoDEM database (Scotese, 2002) and the Paleomap project (Scotese, 2016) to compile a paleogeographic atlas of 114 paleomaps spanning over 600 Ma, covering the paleogeography of the Phanerozoic.

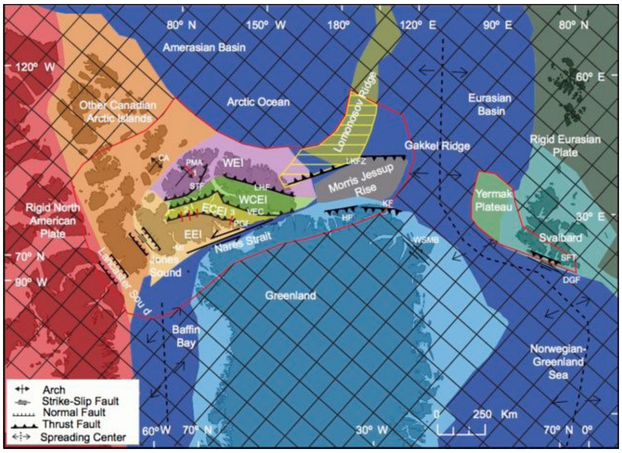

Figure 7. Division of tectonic domains and general structures (at present day), used in reconstruction model. Reproduced from figure 3 of Gion et al. (2017).

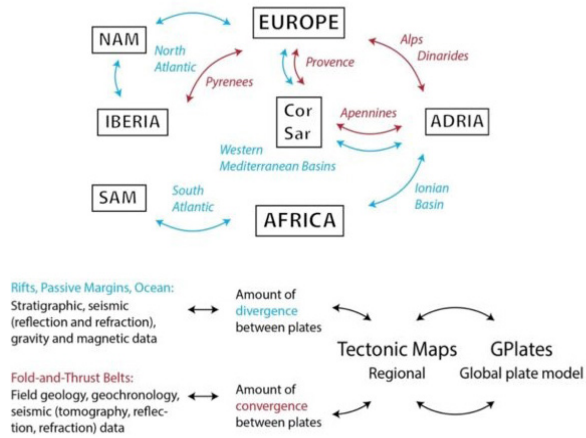

Figure 8. Approach and data used to reconstruct the plate motions. Reproduced from figure 2 of Le Breton et al. (2021).

ArcGIS and GPlates are used to visualise and update the PaleoDEM, and incorporate it into the global database. A review of the major orogenic events is also included in the context of their paleogeographic models.

3.6. Combined approaches

Flament et al. (2014) used two kinematic models that explained the opening of the South Atlantic Ocean. The seafloor spreading data, Bouguer gravity anomalies, continent-ocean boundaries, and deformation constraints were implemented to create a geodynamic model that dated back to 200 Ma.

Matthews et al. (2016b) compiled two previously published models of Late Paleozoic and Mesozoic-Cenozoic to present a global plate model spanning over 400 Ma, with a temporal resolution of 1 Ma. The reference-frame of the Mesozoic-Cenozoic model is updated, and continuity is maintained for the 230–250 Ma time. The model is visualized using GPlates and incorporates continuous and evolving plate boundaries, based on the analysis of the number of plates, plate size distribution, global plate and continental RMS speeds and trench migration through time.

Zhu et al. (2021) presented the tectonic history of the deformation of the Bohai Bay Basin in the Cenozoic by reconstruction using structural, stratigraphic, and depositional age data along with balanced cross-sections. The rigid plate reconstruction was done using GPlates. The linear features were incorporated as vector data (points, lines, and polygons) with their individual rotation poles, and the model followed the theory of continuously closing plates. The basin was treated as a continuously moving polygon, and the regions with minimal deformation were considered rigid blocks. Müller et al. (2019) developed a global model of deforming plates and the progressive evolution of the rifts and orogenes after the onset of the rifting of Pangea (approximately 240 Ma), including failed continental rifts and collision zones, using global tectonics models and previously published models, geological and geophysical data. The model incorporates the COB, crustal thickness data, hot spot tracks and available seismic refraction profiles.

Le Breton et al. (2021) presented a kinematic reconstruction of the tectonic deformation in the Alpine-Mediterranean region during the Alpine orogeny and proposed a best-fit model for the western Mediterranean-Alpine area by compiling the previous reconstruction models, conjugate magnetic anomalies and other geophysical data in the Atlantic Ocean. The tectonic maps and models have been digitized using the GIS and GPlates software to create a model that dates back to 200 Ma. The output provides a base for future reconstructions and modelling in the region around the Alpine orogeny (Figure 8).

4. Applied aspects of GPlates study

4.1. Petroleum exploration

Plate reconstruction has evolved to be an essential tool in hydrocarbon exploration; the evidence of hydrocarbon-bearing basins on a continental margin is leading the geologists to look for similar petroliferous basins on the other side of the rifts. The tectonic relations between the Brazilian and the West African coast have been utilized for prospecting targets along the rift. The conjugate basins have been studied to provide more credibility to the newly discovered sites on the continental margins (Bryant et al., 2012).

Plate reconstruction using GIS has previously been used to indicate petroleum systems on both sides of a plate boundary. For example, Mazumder et al. (2017) reconstructed a probable Gondwana transcontinental rift and studied its implications for hydrocarbon reserves in the basins of Kutch and Saurashtra (Gujarat, India). GIS was used to represent and rotate the structural and stratigraphic elements of the rifted basins into their prerift positions per the published plate tectonic models. It was observed that the sedimentary basins that were assumed to lie along the rift —in Oman, Upper Indus Valley, Madagascar, Ethiopia and Seychelles— should be hydrocarbon-bearing. This implied that a petroleum system might have existed within the rift system in the present day Indian continent. The continuation of a petroleum system should be present in the Saurashtra and Kutch offshore, making these regions prospective for future hydrocarbon exploration.

GPlates can be introduced in such systems to incorporate more datasets and to provide better visualization of the plate tectonic fit. If applied to rift systems, GPlates can give rise to new and improved prospecting criteria for hydrocarbon exploration at the conjugate margins. The possible connection between two basins has immense importance for hydrocarbon exploration and basin modelling. The incorporation of paleotopography using GPlates in basin modelling can produce more reliable prospecting criteria. Implications for heat flow and source rock presence from a full-fit plate tectonic reconstruction give an idea about sediments' thermal history. This can in turn define potential hydrocarbon system (Sandovel et al., 2019).

The tectono-sedimentary evolution of passive rifted margins and establishing continuity between two conjugate marginal basins is an important study for exploring hydrocarbon systems. GPlates, in association with seismic data can be used to construct an extensive tectono-stratigraphic history (Blischke et al., 2019) that would be useful in petroleum exploration.

4.2. Other applied studies

Reconstruction using GPlates has often been used as a tool and a supporting evidence for multidisciplinary studies involving paleobiology, paleoclimate, and mantle studies. Richter et al. (2020) used paleogeographic reconstruction near the Arctic as supporting evidence to study the Cretaceous paleosubduction zone near the Western Gakkel Ridge region and contributed to the tectonic evolutionary history of the area. Heron et al. (2019) used a reconstruction of the Davis Strait region based on velocity azimuth as supporting evidence to study the role of heterogeneities in the crustal and subcrustal lithosphere in deformation and continental suturing. Pollette et al. (2019) presented a study that compares the heat flow values that are collected in situ with those predicted geophysically, and incorporates the regional-scale heat flow data and plate reconstruction of Gondwana during the Jurassic to create the first heat flow map of the region that was previously connected with East Antarctica. The available terrestrial heat flow data from each continent was plotted using GPlates using the continental fit from Matthews et al. (2016b). Further, Gondwana approximately 200 Ma was reconstructed at additional locations in southern Australia and Antarctica with similar heat flow values across plate margins. Davydov et al. (2021) studied the evolution of the biota and the climate during the Permian-Triassic transition in the Russian Kuznetsk basin and created a model using the independent approaches of radio-isotopic CA-IDTIMS U-Pb zircon ages, δ13Corg isotope values, and paleomagnetic proxies. GPlates and QGIS were used to reconstruct the paleogeography during the Permian-Triassic transition for the correlation studies. Note that new microplate boundaries discovered by the geocientists in last few years (e.g., Li et al., 2018; 2019) are yet to be incorporated in the G-plates model. Since microplates, usually irregular-shaped, define a "smaller" plate between two known plates (Topper et al., 2010), reinterpretation of tectonic reconstruction of the microplates remains to be an important exercise.

4.2.1. Deep carbon cycle

Carbon sequestration (review in Shaw and Mukherjee 2022) has been an active research topic in last two decades or so. The deep carbon cycle of the Earth is gaining attention because of this as well. The geodynamic evolution of the Earth has asserted its control over the deep carbon cycle over geologic times. Paleogeographic reconstructions using GPlates have been utilized to provide an insight into the deep carbon cycle of the Earth. Brune et al. (2017) examined the possible connection between continental divergence and the deep carbon cycle based on the massive amount of CO2 release at rift systems by studying the lengths of the continental rifts over the last 200 Ma. Wong et al. (2019) applied the published global plate rotation model that incorporates global paleomagnetic data, seafloor isochrons and other plate motion indicators to visualize plate boundary lengths and estimated the tectonic carbon flux at 1 Ma intervals to create a model for the deep carbon cycle spanning over 200 Ma. Johansson et al. (2018) investigated the effect of the eruption and weathering of large igneous provinces on the deep carbon cycle by combining global plate reconstructions, eruption ages of large igneous provinces, and the global atmospheric CO2 data. The python library pyGPlates has also been used in the study of the deep carbon cycle as well. Müller and Dutkiewicz (2018) studied the periodicities of atmospheric carbon dioxide and the evolution of the crustal carbon reservoir in the context of seafloor spreading and subduction zone migration.

4.2.2. Mineral systems

Morrisson et al. (2020) described how incorporating mineralogical data into plate tectonic reconstructions through platforms like GPlates would further the understanding of the mineral systems in the context of specific tectonic settings and identify mineralization associated with collisional or divergent settings. For instance, subduction-related mineralization would not only be studied in relation to subduction properties and its drivers but also in the spatial and temporal context.

4.2.3. Predicting future supercontinents

Davies et al. (2018) followed the theory of plate movement and Wilson cycle to model four possible scenarios of future supercontinents. Using the present global geologic and crustal data and plate velocities into GPlates, models were created for 200–300 Ma span into the future.

Paleo-latitude calculator: GPlates has recently been applied in paleontological studies as a paleocoorndinate calculator for fossil specimens and rock samples for varied purposes. Table 3 summarizes the key works done by applying GPlates as a paleocoordinate calculator.

Table 4 gives an overall idea about the geographical regions and fields where GPlates have been used, along with the parameters applied. Table 5 presents summary of research particles that have used pyGPlates. Table 6 summarizes the use of the numerical modelling software Badlands in GPlates. Figure 9 shows the regions on a world map where GPlates has been applied using the above mentioned parameters.

5. Conclusion

GPlates has been an integral and efficient tool in visualising models of plate tectonic reconstructions. The advantage of GPlates lies in its user-friendly interface, which supports a wide variety of data. The easy integration of GPlates with ArcGIS or other GIS applications gives it an edge in the field of multidisciplinary studies and opens up new and advanced avenues to carry out the process of reconstruction. Several terrains in the world have been tested with GPlates, and applied geoscientific research has been carried out. For example, plate reconstruction aided by GPlates has helped in correlating more accurately the hydrocarbon-bearing basins at conjugate/continental margins at the West African and the Brazilian coast. A similar work was done to extrapolate Gondwana transcontinental rift in Gujarat, India using GIS. In conjunction with seismic data, GPlates application yielded tectonostratigraphic history of the basin. Other applications of GPlates have been in understanding paleosubduction, continental suturing, incorporation of regional heat flow data in tectonic models,

Table 3. List of studies done using GPlates as paleocoordinate calculator.

Sl. no.	Region	Author	Time	Parameters	Key work
1	South America	Solórzano and Núñez-Flores (2021)	Cenozoic	Previously published models	Evolutionary trends from fossil assemblage database
2	Australia	Kundrát et al. (2020)	Early Createceous	Previously published models	Study of dinosaur feather fossil assemblage
3	Eurasia	Utescher et al. (2021)	Oligocene	Previously published models (hotspot tracks)	Study of spatial vegetation patterns by appliying Plant Functional Types (PFT) and their distribution
4	UK	Pearce et al. (2020)	Late Cretaceous	Previously published models	Study of Biostratigraphy and Chemostratigraphy using palynological analysis
5	Global	Antell et al. (2020)	Paleozoic	PaleoAtlas database	Study of spatial biodiversity patterns from a global database
6	Global	Allen et al. (2020)	Permo-Triassic	PaleoAtlas database	Marine biodiversity and its dependence on geographic distributions
7	Global	Rojas et al. (2021)	Phanerozoic	Paleobiology database	Major biotic transitions through Phanerozoic
8	Global	Zacaï et al. (2021)	Early Paleozoic	PaleoAtlas database	Study of latitudinal diversity gradient in early Paleozoic phytoplankton

Table 4. List of studies done using GPlates using the mentioned parameters.
(*) → Papers where GPlates was used only for paleogeographic maps.
(**) → Studies concerning implications of hydrocarbon systems.
(#) → Plate models supported by GPlates.

Sl. no.	Area	Region	Author	Geological time	Parameters	Purpose	Additional software/ methods
1	America	Isthmus of Panama	Montes, Cardona, et al. (2012)	Eocene	Previously published models	Tectonic evolution	Geochronology, thermochronology
2	America	Isthmus of Panama	Montes, Bayona, et al. (2012)	Cenozoic	Ocean floor anomalies	Tectonic evolution	IAPD 2000
3#	America	northern Andes and southern Caribbean margin	Montes et al. (2019)	Creatceous	Published geologic maps	Relative motion of blocks	GIS
4#	America N		Henderson et al. (2014)	Jurassic	Geological constraints, paleomagnetic data	Tectonic evolution	mantle tomography
5	America N	Queen Charlotte fault,	Schoettle-Greene et al. (2020)	Miocene	Previous models	tectonic evolution	QTQt
6	America N	NW Cordillera	Fuston and Wu (2021)	Cenozoic	Isochrons and Geological constraints	Tectonic evolution	mantle tomography
7	America S	Parnaíba Basin, NE Brazil	Jaju et al. (2018)	Paleozoic	Paleomagnetic data	Paleoclimate reconstruction	
8*	America S	NE Brazil	Bastos et al. (2020)	Early Cretaceous	Previously published models, bathymetry	Paleogeographic reconstruction	
9*	America S		Belén Tomaselli et al. (2021)	Cretaceous	PaleoAtlas database	Paleogeographic reconstruction	
10	America S	Famatinian orogen	Geuna et al. (2021)	E Paleozoic	Paleomagnetic data	tectonic evolution	ArArCalc software for geochronology, IRM-CLG 1.0 software
11	America S		Solórzano and Núñez-Flores (2021)	Cenozoic	Previously published models	Computing paleocoordinates	OLS analysis in R
12	Antarctica		Evangelinos et al. (2020)	Late Oligocene-Miocene	Previously published models	Paleooceanographic configuration	PAST, ChemStation software
13*	Antarctica		Klages et al. (2020)	Cretaceous	Previously published models	Paleogeographic reconstruction	
14	Antarctica		Hochmuth et al. (2020)	Oligocene	Previously published models (paleomagnetic and hotspot reference frames)	Paleobathymetry model	BalPal routine, Seismic stratigraphy
15	Antarctica	Mozambique-Antarctica	Tomasi et al. (2021)	Neo-Proterozoic	Seismic data, Deformation constraints	tectonic evolution	
16	Arctic	Eurekan Orogeny	Gion et al. (2017)	Paleogene	Deformation constraints, previous models	plate model of regional crustal deformation	
17	Arctic	Davis Strait	Heron et al. (2019)	Mesozoic	Previously published models	tectonic evolution	Numerical modelling, ASPECT
18*	Arctic		Hjálmarsdóttir (2019)	Middle Jurassic – Early Cretaceous	Previously published models	Paleogeographic reconstruction	
19*	Arctic	Lomonosov Ridge	Sluijs et al. (2020)	Late Paleocene – early Eocene	Previously published models	Paleogeographic reconstruction	paleothermometry
20	Arctic	Gakkel Ridge	Richter et al. (2020)	Cretaceous	Gravity models	Mantle flow study	Seismic tomography
21	Arctic	Knipovich Ridge	Dumais et al. (2021)	Early Oligocene	Magnetic anomaly	Tectonic evolution	ModMag, Geochemical study
22	Asia	India-Asia	van Hinsbergen et al. (2011)	Cenozoic	Rotation poles	Tectonic evolution	

Table 4. (Continued).

23*	Asia	Indosinian orogeny, Thailand	Arboit et al. (2017)	Early Permian - Late Triassic	Palaeostress magnitude and geomechanical data	Paleostress analysis	calcite twinninganalysis
24*	Asia	Cuu Long Basin, Vietnam	Schmidt et al. (2019)	Cenozoic	Seismic data	Tectonic evolution	Satellite images and Geological maps
25	Atlantic	Barents Sea	Lasabuda et al. (2018)	Cenozoic	Seismic data	Paleoenvironmental reconstruction	Geological maps and mass balance approach
26*	Atlantic	Northern Canadian Cordillera	Enkelmann et al. (2019)	Mesozoic	Previously published models	Tectonic evolution	
27	Atlantic	N.America-Iberia	Peace and Welford (2019)	Jurassic	Deformation constraints	Tectonic evolution	Seismic data
28	Atlantic	Southern north atlantic rift	Peace and Welford (2019)	Mesozoic	Previously published models (hotspot tracks)	Comparing two models	CRUST 1.0
29**	Atlantic	East Orphan, Porcupine, and Galicia Interior basins	Sandoval et al. (2019)	Jurassic	Seismic data	Tectonic and kinematic evolution	MOVE™ software
30	Atlantic	Western Tethys–North Atlantic	Angrand et al. (2020)	Permian-Mid Cretaceous	Paleomagnetic data (previous models)	modifies previous models	Seismic data
31	Atlantic	Galicia Bank	King et al. (2020)	Jurassic	Previously published constraints	Tectonic evolution	Gravity inversion, Surfer software
32	Atlantic	Iberia–Newfoundland	Szameitat et al. (2020)	Paleozoic	Previously published models (age grids)	Restoring paleopositions of magnetic signatures	
33	Atlantic	Gulf of Mexico	Pindell et al. (2021)	Mesozoic	Previously published models	Tectonic evolution	GIS, Geochronology
34	Atlantic	Carribbean	Gómez-Garciá et al. (2021)	Cretaceous	Previously published models, bathymetry	Crustal evolution	3D data models, gravity and magnetic anomalies
35	Atlantic	Isthmus of Panama	McGirr et al. (2021)	Oligocene	Magnrtic anomaly, bathymetry, asesimic ridges and fossil spreading centers	Tectonic evolution	Satellite data, Python
36	Atlantic South	S.America-Africa	Flament et al. (2014)	Jurassic	Combined	origin of topography	CitcomS
37	Atlantic (South)	Rio Grande Rise	Galvão and de Castro (2017)	Createceous	Bathymetry, Gravity and Magnetic Anomalies	Tectonic evolution	OpenGL, GIS
38	Atlantic (South)	Rio Grande Rise and Walvis Ridge	Graça et al. (2019)	Cretaceous	crustal thickness and magnetic anomaly data	Crustal thickness mapping and tectonic evolution	
39	Atlantic South	Patagonia	Suárez et al. (2019)	Paleozoic-Triassic	Geometric fit and coastlines	Tectonic evolution	GIS
40*	Atlantic (South)		Setoyama and Kanungo (2020)	Mesozoic	PaleoAtlas database	Paleogeographic reconstruction	
41	Atlantic (South)		Chauvet et al. (2021)	Mesozoic	Previously published models	Paleogeographic reconstruction	Seismic data
42	Auatralia		Li and Evans (2011)	Late Neoproterozoic	Paleomagnetic data and deformation constraints	Relative motion between Rodinia and Australia	
43	Australia	Aus-Greater India	Gibbons et al. (2012b)	Jurrassic	Gravity and Magnetic Anomalies	Tectonic evolution	mantle tomography
44	Australia	(Banda Sea)	Heine et al. (internet ref)	Jurassic	Flexural slip rstoration	Tectonic evolution	2D and 3D Move structural restoration software
45	Aus and NZ		Müller et al. (2018)	Jurrassic	Lithospheric deformation/ crustal thicknesss	Change in stretching factor modelled through time	
46	Auatralia	S. Australia-E. Antarctica	Pollett et al. (2019)	Jurrassic	Combined	Regional heat flow map	Drill cores
47	Aus/NZ	Lachlan orogen	Schaap et al. (2019)	Paleozoic	Geological data, Magnetic and Gravity anomalies	Tectonic evolution	

Table 4. (Continued).

48	Aus and NZ	Chatham Rise	Riefstahl et al. (2020)	Cretaceous	Previous models	Tectonic evolution	ZP, IGMAS +, Paradigm, GMT
49	Australia		Kundrát et al. (2020)	Early Createceous	Previously published models	Computing paleocoordinates	Palaeolatitude.org
50	Australia	Mentelle Basin	Maritati et al. (2021)	Mesoozoic	Rotation poles	Paleogeographic reconstruction	Geochronology, Seismic data
51	E. Africa	Davie Ridge	Vormann and Jokat (2021)		Paleomagnetic data	Tectonic evolution	
52	Eurasia	Piemont-Liguria Basin	le Breton et al. (2021)	Jurassic	Combined	Tectonic evolution	GIS, SLIM3D
53*	Eurasia		Garibian et al. (2020)	Mesozoic	PaleoAtlas database	Paleogeographic reconstruction	
54	Eurasia		Utescher et al. (2021)	Oligocene	Previously published models (hotspot tracks)	Computing paleocoordinates, Paleogeographic reconstruction	
55	Europe	Goban spur and Newfoundland margin, Ireland	Yang et al. (2020)	Cretaceous	Geophysical and seismic data	Tectonic evolution	Petrel
56*	Europe	W. Karelia, Finland	Davey et al. (2020)	Archean	Geochronology, geochemistry	Paleogeographic reconstruction	
57*	Europe	Wales	Pates et al. 2020)	Ordovician	PaleoAtlas database	Paleogeographic reconstruction	
58	Europe NW	UK	Pearce et al. (2020)	Late Cretaceous	Previously published models	Computing paleocoordinates	PAST software, Geochronology
59	Europe	Ireland	Yang and Welford (2021)	Paleozoic	Seismic data	Tectonic evolution	
60#	Global		Matthews et al. (2016b)	Paleozoic to recent	Combined	Global plate model	
61	Global/ East Asia		James and Schettino (2017)		Combined	Tectonic evolution	GIS
62	Global		Brune et al. (2017)	Cretaceous to recent	Previously published models	Deep Carbon cycle	
63	Global		Johansson et al. (2018)	Paleozoic to recent	Previously published models	Deep Carbon cycle	MATLAB, GMT
64	Global		Davies et al. (2018)	200-300 Ma into the future	Geological features and plate velocities	Models of future supercontinents	Previously published propositions
65#	Global		Gurnis et al. (2019)		Geophysical data	4-D Earth models	CitcomS
66	Global		Wong et al. (2019)	Jurassic to recent	Rotation poles	Deep carbon cycle model	Carbon flux models
67*	Global		Cao et al. (2019)	Paleozoic	Previously published models	Paleogeographic reconstruction	Generic Mapping Tools, Python2.0., HEALPix method
68#	Global		Tetley et al. (2019)	Triassic	global hotspot track observations, net lithospheric rotation (NLR), parameter estimation for paleotrench migration	Plate motion model	
69	Global/ East Asia		He et al. (2019)	Eocene	Prev model (palgeo dataset)	Paleoclimate modelling	GIS
70#	Global		Merdith et al. (2020)	Neoproterozoic to Phanerozoic	Paleomagnetic data and geological constraints	Global plate model	
72	Global		Gallahue et al. (2020)		VOLMIR dtaaset and seismic data	Study of igneous rock volumes in the context of passive margins	
73**	Global		Evenick (2020)	Late Cretaceous	Published resources	TOC paleomaps	
74	Global		Gernon et al. (2021)	Paleozoic	Previously published models	Tectonic evolution	pyGPlates, R

Table 4. (Continued).

75*	Global		Loncke et al. (2020)	Lower Paleozoic	Previously published models	Paleogeographic reconstruction	Chemostratigraphy
76	Global		Loncke et al. (2020)		Previously published models, bathymetry	Tectonic evolution	Generic Mapping Tools software
77	Global		Antell et al. (2020)	Paleozoic	PaleoAtlas database	Computing paleocoordinates	iDigBio platform, R
78#	Global		Crameri et al. (2020)		Previously published models	SZI database	Python, MATLAB, seismic tomography
79*	Global		Baca and Short (2020)	Cretaceous	Previously published models	Paleogeographic reconstruction	
80*	Global		Michel et al. (2020)	Oligocene and Miocene	PaleoAtlas database	Paleogeographic reconstruction	Paleoceanographic data
81*	Global		Turk et al. (2020)	Cretaceous	Previously published models	Measuring paleodistances	Biogeographical models using RASP
82	Global		Allen et al. (2020)	Permo-Triassic	PaleoAtlas database	Computing paleocoordinates	R package iNEXT
83	Global		Dasgupta et al. (2021)		Age of subducting slab	Subduction zone modelling	Numerical modelling
84#	Global		Williams et al. (2021)	Late Paleozoic	Seafloor age	Seafloor age reconstruction	pyGPlates
85#	Global		Merdith et al. (2021b)	Jurassic	Previously published models	Extract spreading lengths	Crustal and lithological data
86	Global		Cao et al. (2021)	1 Ga to recent	Previously published models	Evolution of mantle flow	CitcomS, cluster analysis, pyshtools
87	Global		Scotese (2021)	Phanerozoic to recent	PaleoDEM database	Paleogeographic reconstruction	
88	Global		Rojas et al. (2021)	Phanerozoic	Paleobiology database	Computing paleocoordinates	Hexbin R-package
89	Global		Zacaï et al. (2021)	Early Paleozoic	PaleoAtlas database	Computing paleocoordinates, Paleogeographic reconstruction	
90	Global		Kroner et al. (2021)	Paleozoic	Kinematic parameters from Previously published models	Tectonic evolution	Geological data, Euler poles
91	Gondwana	Iapetus and Rheic oceans	Domeier (2016)	Early Paleozoic	Deformation constraints, geological and paleogeographicdata	Tectonic evolution	
92	Gondwana		Gianni et al. (2019)	Mesozoic	Previously published models	Mantle modeling	Seismic Tomography, geochronological datasets
93	Gondwana	India-Australia-Antarctica	Gupta et al. (2021)	Mesoozoic	Previously published constraints	Tectonic evolution	
94	Gondwana	Alps	Siegesmund et al. (2021)	Ediacaran to Paleozoic	PaleoAtlas database	Tectonic evolution	Geochemistry
95	Gondwana		Oriolo et al. (2021)	Paleozoic	Paleomagnetic data	Paleogeography	
96	Gondwanaland	Zealandia	Yoshida et al. (2020)	Cretaceous	Previously published models	Tectonic evolution	Seismic Tomography, Numerical model using ConvGS
97	India-Eurasia		Gibbons et al. (2015)	Meso-Cenozoic	Paleomagnetic and geological constraints	Tectonic evolution	GMT, Timescale creator
98	Indian	Australia-Antarctica	Williams et al. (2011)	Cretaceous	Combined	Tectonic evolution	GMT, ArcGIS
99	Indian	Berakup of East Gondwana	Gibbons et al. (2013)	Cretaceous	Magnetic and Gravity anomaly data	Tectonic evolution	GEODAS data, GMT
100	Indian	Australia-Antarctica	Whittaker et al. (2013)	Cretaceous	Combined	Tectonic evolution	GMT, ArcGIS
101	Indian	Burma Terrane	Westerweel et al. (2019)	Creatceous	Paleomagnetic data	Tectonic evolution	GIS
102	Indian	India-Asia	Parsons et al. (2020)	Triassic	Seismc tomography, geological and geophysical dataset	Tectonic evolution	ArcGIS, Google Earth, SubMachine software

Table 4. (Continued).

103	Indian	India-Sri Lanka	Ratheesh-Kumar et al. (2020)	Createceous	Magnetic anomaly	Tectonic evolution	Flexure inversion modelling
104	Indian		Parnell-turner et al. (2020)	Cenozoic	Crustal age and previous rotation models	Tectonic evolution	Bathymetric data
105	Indian		van Hinsbergen and Schouten (2021)		Published rotation poles and polygons	Predicting future supercontinents	Geological data
106*	Laurentia		Saylor and Sundell (2021)	Triassic	PaleoAtlas database	Paleogeographic reconstruction	Geochronology
107	Mediterranean	Aegea-West Anatolia	van Hinsbergen and Schmid (2012)	Eocene	Slab restoration, rotation poles	Tectonic evolution	
108	Mediterranean		van Hinsbergen et al. (2014)	Cenozoic	kinematic constraints from previously published models	Subduction zone modelling	
109	Mediterranean		Menant et al. (2016)	Late Cretaceous	Combined	Tectonic evolution	GIS database
110	Mediterranean	Tyrrhenian Basin	Turco et al. (2021)	Tertiary	Deformation constraints	Tectonic evolution	
111*	N..Hemisphere		Mitrovica et al. (2020)	Plio-Pleistocene	Previously published models	Paleopole and Paleogeographic reconstruction	Mantle viscosity profile
112	N. Hemisphere	Kuznetsk Basin, Siberia	Davydov et al. (2021)	Permo-triassic	Paleomagnetic data	supporting evidence	GIS, Bchron, CONOP softwares
113	NZ	Koumac-Gomen area, New Caledonia	Dallanave et al. (2020)	Eocene	Magnetostratigraphic data, previous models	Magnetostratigraphy	
114	Pacific	Mongol-Okhotsk Ocean	van der Voo et al. (2015)	Jurassic	Paleomegnetic data, APWP	Tectonic evolution	Seismic and tomographic data
115	Pacific	S. China sea	Bai et al. (2015)	Late Cretaceous	Combined	Tectonic evolution	
116	Pacific	Philippine Sea	Wu et al. (2016)	Cenozoic	3D unfolded slab data, previous models	Tectonic evolution	Gocad software, AreaErrorProp, GMT
117	Pacific	W. Pacific	Liu et al. (2017)	Jurassic	strain recovery, geological and seismic tomography constraints	Tectonic evolution	
118*	Pacific	Bohai Bay Basin	Xu et al. (2019)	Cenozoic	age and thickness of thermal lithosphere data	Thermal lithosphere evolution	Boreholes, crustal data
119*	Pacific	South China	Wang et al. (2019)	Triassic	Previously published models	Paleogeographic reconstruction	Geochronology
120	Pacific	W.N.America-E. Pacific	Clennett et al. (2020)	Jurassic	Paleomagnetic data	tectonic evolution	Mantle tomography
121	Pacific	South China sea	Cao et al. (2020)	Jurassic	Crustal deformation constrains/Geological and Geophysical data	Tectonic evolution	
122	Pacific	S. China sea	Bai et al. (2020)	Cenozoic	Geophysical data, crustal streching parameters	Tectonic evolution	
123*	Pacific	S. China	Li et al. (2020)	Paleozoic	PaleoDEM database	Paleogeographic reconstruction	Geochronology
124	Pacific	S. China sea	Hou et al. (2020)	Late Permian	Statigraphic sequence, global plates motion model	Paleogeographic reconstruction	ArcGIS
125	Pacific	Ryukyu subduction zone	Suenaga et al. (2021)		Heat flow, mantle flow velocity	Earthquake investigation	Generic Mapping Tools, ParaView, Perple_X, Stag3D
126	Pacific	Bohai Bay Basin	Zhu et al. (2021)	Cenozoic	Rotation poles	tectonic evolution	CitcomS
127	Pacific	Kanto Mountains, Central Japan	Tominaga and Hara (2021)	Jurassic	Magnetic anomaly	Paleogeography	Geochronology, Isoplot/ Ex 4.15 software
128*	Rodinia	W. Africa	Antonio et al. (2021)	Proterozoic	Previously published models	Paleogeographic reconstruction	Isoplot, Forcot

Table 5. Use of pyGPlates in tectonic research.

Sl no.	Area/approach/aim	Author(s)	Purpose	Main outcome
1	Earth's mantle (global model)	Arnould et al. (2020)	Time-dependent motion of mantle plume conduits	Link between plume dynamics and spreading rate
2		Boyden et al. (2011)		
3	Global model	Brune et al. (2018)	Combined Study of relative extension velocity and local rift trend	Global mean rift obliquity since 230 Ma is 34°
4	Global numerical model	Brune et al. (2017)	Tectonic CO2 release rates through time	160–100 Ma and after 55 Oa there were enhanced rifting matching with greenhouse climate
5	Machine learning approach	Butterworth et al. (2015)	How back-arc magmatism led to porphyry formation	Magmatism and ore genesis linked with a number of tectonic parameters
6	Spatiotemporal data mining	Butterworth et al. (2016)	How subduction leads to genesis of Cu-ores	Tectonics and ore genesis linked in terms of several tectonic parameters
7	Digital paleogeographic reconstruction	Cao et al. (2017)	Restoring paleogeographic maps to their present positions	Mode of plate reconstruction fundamentally contributes to changes in land areas
8	Compilation of geological and paleomagnetic data	Collins et al. (2021)	Late Tonian reconstruction related to the Mozambique Ocean	Plates reorganized and shifted continents in the southern hemisphere and developed an all-northern hemispheric ocean in the past
9	Spatio-temporal machine learning method	Diaz-Rodriguez et al. (2021)	How tectonics controls mineralization	Copper mineralization prediction maps produced
10	Total CO2 flux from incipient mid-ocean ridge and large igneous provinces from the North Atlamtic Ocean	Gernon et al. (2021a)	Seafloor production rate in the past	Lithospheric mantle carbon flux estimated for the past. Anomalous CO2 fluxes during rifting confirmed.
11	Thermo-mechanical simulation	Gernon et al. (2021b)	What controls kimbertlie magma to come out	Most kimberlites billion years back extruded approximately 25 Ma after the continents broke
12	Data mining coupled with other approached	Gernon et al. (2021c)	Link between tectonics and atmospheric composition	Rapid drawdown of CO2 related to arc weathering fixed surface temperatures on the Earth
13	Hiatus of paleogeographic maps used to produce interregional maps of the past	Hayek et al. (2020)	Digital information on maps from open access sites compiled	Stronger upper mantle with respect to the upper mantle predicted
14	Cross correlation and multivariate regression	Hu and Gurnis (2020)	Subduction duration linked with several other parameters in tectonics	Subduction history linked with slab dip
15	CitcomS software	Hu et al. (2022)	Quantification of changes in Pacific plate's movement	Change on motion of Pacific Plate and drift of hotspot plausibly controlled the Hawaiian-Emperor Bend
16	3D dynamic subduction models	Hu et al. (2021)	Climatic and tectonic roles in the growth of the Andes mountain	Migration of Juan Fernandez Ridge towards south acted as a barrier trench sediments flowing towards N. Thickness of the trench fill sediment is an important point in Andean orogeny.
17	Automatic, tracer-based algorithm	Karlsen et al. (2020)	Seafloor age models for the ocean basins of the Paleozoic that have been destroyed	The sea level was high when Pangea was assembled.

Table 5. (Continued).

18	Use of kinematic data (rotation issues) to comment on rifting	Merdith (2017)	Establishing the first topological plate model of the Neoproterozoic of the whole Earth	Supercontinent develops when a global peak of continental arc happens. Amalgamation of Gondwana defines Phanerozoic supercontinent cycle.
19	Deep-time reconstructions using absolute plate movement deduced from paleomagnetic data	Merdith et al. (2017)	Plate kinematics deduced from different reconstructions	The model for rifting of the western Rodinia and transition to eastern Gondwana are refined.
20	pyBacktrack software	Müller et al. (2018)	Backtracking of the past water depth of oceans	Training and examples undertaken
21	Global plate model and oceanic paleo-age grids combined	Müller and Dutkiewicz (2018)	Evolution of oceanic crustal carbon reservoir in past 230 My	Subduction zone migration drives the peridocites of seafloor spreading
22	Geotectonic analyses	Brune et al. (2016)	Global rift kinematics	Plates accelerate before continents rupture. Significant margin area developed during each phase
23	Continuous and cross-wavelet analyses and wavelet coherence studies	Pall et al. (2017, 2018)	How much the carbonate-intersecting subduction zones in the past contributed to atmospheric CO2	Models of CO2 flux between shallow and deep carbon reservoirs can now be attempted
24		Park (2020); Park et al. (2021)	Paleogeographic reconstruction of Large Igneous Provinces (LIP)	No correlation between planetary weatherability of LIPs and Earth's (non)glacial climate
25	Paleogeographic models explained in terms of paleomagnetic compilations	Swanson-Hysell (2021)	Better tectonic model of Laurentia	Mobile lid plate tectonic mechanisms have been operating since last 2.2 Ga
26	Absolute plate motion models and statistical analyses employed	Tetley (2018); Tetley et al. (2019)	tectonically compliant, data-optimized global absolute reference frames from 220 Ma onward is presented	Absolute plate movement since Pangea: net lithospheric rotation approximately 0.05° Ma-1, absolute paleo trench migration velocity approximately 27-mm y-1
27	Numerical models compared with subduction histories obtained from reconstruction	Ulvrova et al. (2019)	Suitable locations for development of new subduction zones and their (de)activation	Subduction initiates and end s nonrandomly. Subduction zones pause near the continental margins. Intra-oceanic subduction initiates more favourably during supercontinent assembly
28	Compilation of paleopoles of high-accuracy followed by their statistical analyses	Wu et al. (2020)	How Gondwana, Laurentia and Baltica amalgamated	Apparent polar wander were revised: Pange probably initiated approximately 400 Ma as Laurussia collided with Gondwana promontary

Table 6. Use of Badlands software in GPlates.

Sl no.	Author(s)	Purpose	Main outcome
1	Harrington et al. (2019)	Surface processes working on the Australian continent	During the early Mesozoic elevation increased to approximately 500 m. This was coeval to relatively low erosion rates.
2	Salles et al. (2021)	Landscape evolution of Sundaland in last 1 Ma	Fast evolving physiography can promote Quaternary biodiversification
3	Yang and Smith (2019)	3D structural and geomorphic model generation for the Gippsland Basin	Models simulated evolution of the carbonate shelf sediments, sub-marine channels and anticlines.
4	Zahirovic et al. (2019)	Landscape evolution of Australian continent	4D digital landscape evolution simulated while linked with reconstructions, mantle flow, and eustasy

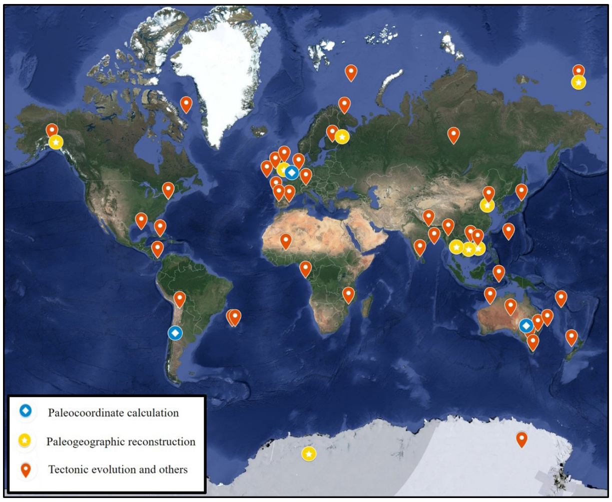

Figure 9. Locations where GPlates has been used, marked on a world map.

paleogeographic model generation along with QGIS, Earth's deep carbon cycle, mineralization in association with tectonics spatially and temporally and in paleolatitude calculation that has been useful in paleontological studies.

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