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# Towards adaptable, interactive and quantitative paleogeographic maps

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## Abstract

A variety of paleogeographic atlases have been constructed, with applications from paleoclimate, ocean circulation and faunal radiation models to resource exploration; yet their uncertainties remain difficult to assess, as they are generally presented as low-resolution static maps. We present a methodology for ground-truthing paleogeographic maps, by linking the *GPlates* plate reconstruction tool to the global Paleobiology Database and a Phanerozoic plate motion model. We develop a spatio-temporal data mining workflow to compare a Phanerozoic Paleogeographic Atlas of Australia with biogeographic indicators. The agreement between fossil data and paleogeographic maps is quite good, but the methodology also highlights key inconsistencies. The Early Devonian paleogeography of southeastern Australia insufficiently describes the Emsian inundation that is supported by biogeography. Additionally, the Cretaceous inundation of eastern Australia retreats by 110 Ma according to the paleogeography, but the biogeography indicates that inundation prevailed until at least 100 Ma. Paleobiogeography can also be used to refine Gondwana breakup and the extent of pre-breakup Greater India can be inferred from the southward limit of inundation along western Australia. Although paleobiology data provide constraints only for paleoenvironments with high preservation potential of organisms, our approach enables the use of additional proxy data to generate improved paleogeographic reconstructions.

## 1 Introduction

The geography of continents has varied considerably through time, driven by plate tectonic processes, crustal thickening and thinning, erosion, sedimentation, and global and regional sea level fluctuations (Miller et al., 2005; Müller et al., 2008), driving both biological radiations and occasional mass extinctions (Hallam and Cohen, 1989; Hallam and Wignall, 1999; Stanley, 1988). In particular, the Mesozoic amalgamation and subsequent dismemberment of the Pangean supercontinent has played a vital role in the paleogeographic, paleobiological, tectonic and climatic evolution of the planet as it resulted in the opening and closure of oceanic gateways that regulated and impacted climate patterns (Cocks and Torsvik, 2002; Scotese et al., 1999; Torsvik and van der Voo, 2002; Golonka et al., 2006; Seton et al., 2012). The ability to create interactive digital models of paleogeography enables the estimation of land and ocean distributions that can be linked to paleo-climate simulations as demonstrated by Gyllenhaal et al. (1991), Ross et al. (1992), Donnadieu et al. (2006) and others. A variety of global and regional paleogeographic atlases have been constructed, but their differences and uncertainties are difficult to assess. Conventional paleogeographic reconstructions are static maps, often with poor temporal and spatial resolutions and usually tied to one plate motion model. Such models tend to fall short in documenting the wide range of source data and reasoning for their interpretations, i.e. the "decision tree" that led to a given set of published maps is usually unknown, including the interpretative weighting of different data types leading to a given interpretation of facies boundaries, paleocoastlines or outlines of mountain belts. Traditional paleogeographic maps are superimposed on specific plate tectonic reconstructions based on paleomagnetic data, faunal data (Cocks and Torsvik, 2002) or reinterpretations of existing paleogeographic reconstructions (Ford and Golonka, 2003; Golonka, 2007). However such maps quickly become outdated as plate motion models are refined and proxy data is improved. Paleogeographic maps are published infrequently and are typically difficult to replicate, modify and use to constrain the evolution of regional basins with numerical simulations.

Using the *GPlates* plate-reconstruction tool, we link the paleobiological data to a global plate motion model that spans the entire Phanerozoic. We focus on Australia to test our methodology, because a regional paleogeographic atlas for Australia is publicly available in digital vector graphics form (Langford et al., 2001), spanning the last 550 million years. An equivalent atlas with global coverage does not yet exist in the public domain. The Paleogeographic Atlas of Australia (Langford et al., 2001) is a digital compilation where both the input data and the paleogeographic interpretation are provided freely online, making this an exemplary case that enables further research and development in the field. There are 70 time slices that cover the entire Phanerozoic, with interpretations largely based on lithological indicators of paleoenvironments (Table 1), structural and tectonic histories and other geological arguments from outcrops and well data. The complete temporal coverage of the Phanerozoic results in a consistent approach to interpreting the changing environments of the entire Australian continent, while the digital provision of input data and subsequent interpretations make this paleogeographic model testable and expandable. To complement the paleogeographic model, we use biogeographic indicators embedded in the open-source community Paleobiology Database that contains entries for almost 130 000 fossil collections and over one million individual fossil occurrences with global coverage. It is a growing resource that is regularly updated, meaning that paleogeographic models can be made to be adaptable rather than presented as static maps.

We integrate the paleogeographic model with a Phanerozoic plate reconstruction model using *GPlates* in order to uncover spatio-temporal correlations and test the fidelity of the existing paleogeographic model in the context of biogeographic indicators from paleobiology. Our paleogeographic reconstructions can be easily linked to alternative plate motion models, have flexible spatial and temporal resolutions, and can be updated interactively. Our paleogeographic interpretations are testable and replicable as the paleogeography model and paleobiology data are made available in digital form in the Supplement. We use a data mining approach to expose the relationships between the fossil collections and the underlying paleogeography in order to identify inconsistencies and therefore help improve the paleogeographic model. The approach can also be used to refine plate fragmentation models by helping to delineate continental rifting episodes linked to inundations that are recorded in the paleogeography.

## 2 Methods

### 2.1 Phanerozoic plate reconstructions

We base our Phanerozoic relative plate motions on the rotation model made available in the supplementary section of Golonka (2007), and use block outlines based on terrane boundaries used in Seton et al. (2012) and interpretations of magnetic and gravity anomalies. Paleozoic plate motions are based on continental paleomagnetic data due to the absence of preserved seafloor spreading histories. Although paleomagnetic data on continents do not provide paleo-longitudes, the relative plate motions can be inferred from commonalities in the apparent-polar wander (APW) paths (van der Voo, 1990). If two or more continents share a similar APW path for a time period, then it can be inferred that these continents were joined for these times. In the ideal world such APW paths would coincide perfectly, but due to the inherent uncertainties and errors in paleomagnetic measurements, we assume that the clustering of paleo-poles indicates a common tectonic history between two or more plates during Paleozoic times. Similarly, tectonic affinities can be deduced from the continuity of orogenic belts, sedimentary basins, volcanic provinces, biogeographic indicators and other large-scale features across presently-isolated continents (Wegener, 1915).

We assign motions to Africa, as the base of our rotation hierarchy, for the Phanerozoic based on the smoothed APW spline path from Torsvik and van der Voo (2002). All continents that moved independently in the absolute reference frame (i.e. relative to the spin axis) from the Golonka (2007) model were recalculated as equivalent relative rotations to a conjugate neighbouring plate, connected hierarchically in our plate circuit as described in Fig. 1. The paleobiogeography is used to test the plate motion histories, and more specifically the evolution of the rift zones resulting from initial Gondwana breakup.

### 2.2 Paleobiology database

The Paleobiology Database (http://paleodb.org) is a compilation of global taxonomic data covering deep geologic time. Fossil collections were downloaded in four groups on 6 October 2011: general (43 878), carbonate marine (34 542), siliciclastic marine (21 576) and terrestrial (22 385). Metadata for each fossil collection were preserved; including the source, present-day co-ordinate, temporal range, lithology of host rock, paleoenvironment, taxonomic descriptors, the collection method and many others (see Supplement). Only collections with temporal and paleoenvironmental assignments were included, with a total of 122 381 fossil collections. Fossil data were assigned GPML (GPlates Mark-up Language) attributes such as appearance and disappearance ages based on the fossil collection's temporal range (Fig. 2). Assemblages were assigned Plate IDs based on their location within present day continental polygons in order to reconstruct the past positions of the fossil collections.

### 2.3 Data mining

The paleogeography and biogeography of Australia was embedded within the global Phanerozoic plate reconstructions. Fossil collections and the Australian paleogeography were reconstructed in *GPlates* at 1 Myr intervals and were used as the seed dataset for extracting the paleogeography (Fig. 3). The spatio-temporal associations between the paleogeography and biogeography through time were analysed to highlight inconsistencies with the aim of improving the paleogeographic model. Inconsistencies between the paleogeographic maps and biogeographic indicators were highlighted for the Emsian paleogeography of southeastern Australia using workflows in the statistical analysis package *Orange* (see Supplement). The raw fossil collection data was assumed to be a true representation of the paleoenvironment at the reconstructed time, while the paleogeography is an interpretation of other raw data, including lithofacies and volcanic histories. For example, paleogeographic regions that indicated land environments where multiple biogeographic indicators robustly suggested a marine environment were treated as inconsistencies requiring refinement of the paleogeographic model.

## 3 Results

The linked plate tectonic, paleogeographic and biogeographic reconstructions are presented for the Phanerozoic in 50 Myr intervals (Fig. 4). By the end Cambrian, Australia was part of the eastern Gondwana megacontinent and spanning equatorial latitudes. The easternmost Australian continent developed in the Paleozoic, marked by the Tasman Line that separates the western cratonic portion of the continent from the younger lithosphere to the east. The northern margin of Gondwana was composed of the east Asian terranes, including North China, South China, Tarim, Tibet, Indochina and the Cimmerian super-terrane. These terranes consecutively detached, to open and subsequently consume the Tethyan oceans, and amalgamated in the northern hemisphere to form the Eurasian continent (Metcalfe, 1994). The breakup of Pangea continued with the dispersal of Gondwana continents, with India and Australia detaching from Antarctica in the Cretaceous in a generally northward trajectory (Fig. 4).

### 3.1 500 Ma (Cambrian)

During the earliest Phanerozoic, Australia is located at equatorial latitudes. Fossil data are sparse globally in the Cambrian and the Paleogeographic Atlas of Australia (Langford et al., 2001) is incomplete during this time. The eastern shelf of Australia is an abyssal environment at this time (Fig. 4a), with an east-west band of shallow marine environment through the central portion of the continent to form the future outline of the Tasman Line (Fig. 5). Fossil assemblages indicate a marine environment, which largely follows the outline of the marine environment from the paleogeographic model.

### 3.2 450 Ma (Ordovician – Silurian)

Global fossil data predominantly indicate marine environments in the Ordovican and Silurian. Based on the Paleogeographic Atlas of Australia, a bathyal-abyssal environment is present along eastern Australia, whilst shallow marine and coastal depositional environments are distributed in an east-west band across the continent (Langford et al., 2001). Available paleobiology data correlate well with Australian paleogeography reconstructions, indicating a marine environment in eastern Australia based on the presence of basinal (siliciclastic), carbonate indeterminate, and deep subtidal biogeographic data at 450 Ma (Fig. 4b).

### 3.3 400 Ma (Devonian)

Inundation of the present day Australian continent has reduced, with the eastern shelf of Australia classified as a bathyal-abyssal environment and an area of shallow marine towards the central portion of the continent (Fig. 4c). Paleobiology indicators correlate well with the paleogeographic data; fossil data implies a marine environment along the present day east coast of Australia, with fossil environments such as platform/shelf margin reef, basinal (siliciclastic), carbonate indeterminate, and intrashelf/intraplatform reef. Global fossil data is denser than in the Cambrian and predominantly indicative of marine environments including slope, reef, buildup or bioherm, carbonate and shallow subtidal inlet environments.

Biogeographic data correlates well with Australian paleogeography; the eastern margin is classified as marine bathyal-abyssal and marine shallow, and fossil assemblages similarly indicate a marine depositional environment at this time, including carbonate and basinal (siliciclastic) settings. Fossil data is available for most of the eastern inundated areas of the Australian margin and is sparse for the remainder of the continent, largely due to the erosional conditions on land. An Emsian (395 Ma) paleogeographic reconstruction (Fig. 6a) highlights the potential benefits of using biological indicators of paleoenvironment, as there are significant mismatches between the proposed

"Land environment unclassified" and the marine fossils (Fig. 7), particularly in Victoria. The fossils have good temporal constraints at Stage level, indicative of Early Devonian age, with a number of them more specifically Emsian in age based on conodont horizons – namely *Eognathodus trilinearis* and *Polygnathus dehicens*. The Emsian fossils are found in the Bell Point, Buchan Caves and the Waratah Limestones with shell and skeletal fragments. The Early Devonian fauna in central Victoria are found in the Humevale formation containing echinoderm fragments. Unfortunately, there are no wells in the Petroleum Wells Database for this region that penetrate Devonian strata to help further refine the extent of inundation.

### 3.4 350 Ma (Carboniferous)

Shallow marine environments remain along eastern Australia (Langford et al., 2001), and spatially corresponding fossil assemblage data support a marine environment, based on shallow subtidal, carbonate and marine indeterminate indicators at 350 Ma (Fig. 4d). The remaining paleogeography of Australia is largely unclassified, with a region of an erosional environment in Central Australia, coincident with the Alice Springs Orogeny (Langford et al., 2001). Global biogeographic data coverage for this time slice is poor and predominantly indicates marine associated environments.

### 3.5 300 Ma (Carboniferous – Permian)

Fossil data coverage is poor globally, with only one fossil data point located within the Australian continent at 300 Ma (Fig. 4e). This fossil assemblage indicates a lacustrine setting, which may be the local base level (sedimentary depocentre) linked to the nearby erosional setting in the paleogeographic model. However insufficient paleobiology data are available to define the extent of the lacustrine environment. Biogeography indicates a deep-water environment off the west coast of Australia, which correlates well with the bathyal-abyssal marine environment in the paleogeographic model. Inundation along the western margin of Australia did not extend south of the present-day

Wallaby Zenith Fracture Zone until the separation of Greater India from Australia in the Cretaceous.

### 3.6 250 Ma (Permo – Triassic boundary)

Biogeographic data coverage is abundant globally, however Australia is poorly represented at this time interval. Based on available biogeographic data, it is indicated Australia has a fluvial-based environment along its present day eastern coast at 250 Ma (Fig. 4f). This correlates with paleogeographic data, which indicates a depositional fluvial-lacustrine environment (Langford et al., 2001), however insufficient biogeographic data is available to determine the extent and shape with published paleogeography. The remaining paleogeography of Australia at this time interval is primarily unclassified.

### 3.7 200 Ma (Triassic – Jurassic)

At this time Australia is located in temperate latitudes (~30 to 60° S). Fossil assemblages located on the Australian west coast indicate carbonate and “reef, buildup or bioherm” environments at ~200 Ma (Fig. 4g) correlating with the coastal depositional and shallow marine environments in the paleogeography. This is consistent with the rifted margin setting of NW Australia, related to the opening of the Meso- and Neo-Tethys with the detachment of Lhasa and Argoland, respectively, from the northern Gondwana margin.

### 3.8 150 Ma (Jurassic)

Biogeographic data coverage is globally rich, especially in the northern hemisphere, however only a single data point is present within Australia at 150 Ma (Fig. 4h). Based on this sole data point, a fluvial environment, which correlates with the paleogeographic environment described by the Paleogeographic Atlas (Langford et al., 2001).

### 3.9 100 Ma (Cretaceous)

The paleobiology data is more comprehensive for this time interval, and suggests vast expanses of terrestrial environments in the northern hemisphere (100 Ma, Fig. 4i). Fossil data indicates two discrete marine and carbonate environments within the present-day Australian continent; located in the north-east (Queensland) and in the centre of the continent (South Australia). The eastern band represented in biogeography indicates terrestrial and fluvial environments transitioning into a carbonate marine setting. The paleogeographic descriptor of both areas is unclassified, suggesting that the paleogeographic model for this region can be refined with biogeographic indicators. The initiation of Gondwana breakup between Greater India, Australia and Antarctica in the Cretaceous is observed in the propagating inundation of the west Australian margin.

### 3.10 50 Ma (Paleogene)

Biogeographic indicators are sparse within Australia, and available data suggests terrestrial, marine and coastal indeterminate environments along the continental margin (50 Ma, Fig. 4j). The paleogeography of Australia is predominantly indicated as an erosional land environment, with depositional areas of fluvial environments throughout. The location of biogeographic indicators corresponds to paleogeographic descriptors.

### 3.11 Recent (Quaternary)

Fossil assemblages in Australia are distributed along the continental margin, and indicate coastal, marine, and foreshore environments (Fig. 4k). The Paleogeographic Atlas has characterised Australia as predominantly an erosional land environment, therefore the locations of coastal, foreshore and marine fossil assemblages along the present-day coastline correlate well with the paleogeographic model.

## 4 Discussion

Linking the paleogeographic history of Australia with biogeographic indicators from the Paleobiology Database demonstrates how a paleogeographic model can be tested and potentially improved using empirical, qualitative and quantitative approaches. Highlighting associations between the biogeography and paleogeography allowed us to highlight inconsistencies between raw data (fossil collections) and the paleogeographic reconstructions that did not draw upon the global paleobiology during its construction. Although the data coverage by paleobiology is imperfect for Australia in comparison to Eurasia and North America, it is an exemplary first-order tool to constrain the evolution of continental inundation histories in the Phanerozoic.

### 4.1 Refining paleogeographic models of Australia using paleobiology

The paleogeographic evolution of Australia is punctuated by a number of significant periods that include the Paleozoic growth of the eastern Australian continent and the inundation of Australia in the mid-Cretaceous from the Late Aptian to the Campanian (Gurnis et al., 1998).

### 4.2 Early Devonian (∼ 419–393 Ma)

Biogeographic indicators that have a well-defined temporal range and paleoenvironmental association can be used to refine existing models of paleogeography. As an example of such an approach, we propose that the inundation of Victoria (VIC) and a portion of New South Wales (NSW) in the Early Devonian lasted until at least the Emsian. We interpret that the marine deposition at the Yass Shelf formed a north-south marine corridor that separated the Snowy Mountains Block from the mainland (Fig. 6b and c). The Devonian outcrops at present-day suggest sedimentation continued into the Emsian, and is largely consistent with the interpretations of Webby (1972) and Veevers (2004) as well as the north-south geometry of the convergent margin along eastern NSW in the Paleozoic (Aitchison and Buckman, 2012). Our results indicate that the shallow marine setting persisted until the onset of the Tabberabberan Orogeny (390–380 Ma) in the Middle Devonian (Collins, 2002; Gray and Foster, 1997).

### 4.3 Cretaceous (145–65 Ma)

The Cretaceous was a significant period of marine inundation in Australia; maximum flooding occurred during the late Aptian to early Albian (120 to 110 Ma) and had predominantly eased by the Campanian (80 to 70 Ma) (Gurnis et al., 1998). Such flooding occurred across large expanses of the continental region east of the cratonic portion of Australia marked by the Tasman Line. Australia experienced maximum flooding in the late Aptian to Early Albian (~ 120 to 110 Ma) along the eastern continental margin (Gurnis et al., 1998). The northeastward motion of Australia over a descending Pacific-derived slab induced a strong negative dynamic topography signal that accentuated flooding from the mid-Cretaceous sea level highstand (DiCaprio et al., 2009; Gurnis et al., 1998; Heine et al., 2010). Well-constrained models of paleogeography are an important validating mechanism for numerical models of dynamic topography, as demonstrated by Gurnis et al. (1998) in the study of the Cretaceous inundation of Australia (Fig. 8). Subsidence from dynamic topography is distinguishable from loading-induced subsidence as it can be reversed if the negative dynamic topography signal diminishes (Gurnis et al., 1998). In the case of Eastern Australia, a Pacific-derived slab sinking beneath eastern Australia imparts up to 350 m of predicted subsidence from geodynamic models on the region underlying the Eromanga Basin between 120 and 110 Ma, but this effect diminishes by 60 Ma as the depth of the sinking slab increases due to the lower viscous coupling between the slab and the lithosphere. As a result, the inundation of eastern Australia retreated due to ~ 200 m of uplift caused by the waning negative dynamic topography signal in an overall eustatic sea level highstand (Seton et al., 2009). The Paleogeographic Atlas indicates inundation in the north-east of the Australian continent from 139 Ma; this flooding progressively covering a large portion of eastern Australia and peaking at ~ 123 Ma. The bathyal-abyssal environments (water deposition $>200$ m) retreat significantly by 110 Ma (Fig. 8), leaving a shallow marine setting that disappears by 100 Ma to be replaced by fluvial and other terrestrial depositional environments. Paleobiology data largely correlates with the paleogeographic model, but suggests that shallow marine settings may have persisted in pockets beyond 100 Ma. Minimal inundation is present at 90 and 80 Ma, and sparse paleobiology data is available for these times, suggesting that the negative dynamic topography signal diminished by ~ 100 Ma or that eustatic sea levels fell to induce a marine regression. Additionally, the inundation history is recorded in the fossil collections from the Eromanga Basin, with a distinct peak of fossil preservation coinciding with the Cretaceous inundation (Fig. 9).

### 4.4 Testing plate motions using paleogeography and biogeography

Paleogeography and biogeography embedded within plate reconstructions can be used to uncover inconsistencies and help refine the plate motion model. The Cretaceous period records significant changes in the tectonic forces acting on the Australian plate, largely driven by the breakup of Gondwana and the subduction of Pacific material along Australia's eastern margin (Veevers, 2012). The relative plate motions suggest rifting between Australia and Greater India began at ~ 165 Ma, consistent with interpretations of seismic sections that indicate rift-related normal faulting penetrated Late Jurassic sedimentary sequences (Song and Cawood, 2000) and syn-rift sediments in the southern Perth Basin (Veevers, 2012). However, the rift-related inundation of this margin occurs much later at ~ 139 Ma based on the paleogeographic model. The discrepancy between the Late Jurassic onset of rifting and delayed submergence may be accounted for by the oblique style or rifting, which resulted in abundant strike-slip faulting (Song and Cawood, 2000), and therefore relatively little lithospheric extension for much of the rift phase, thus delaying subsidence and inundation until a few million years before breakup. Additionally, seafloor spreading initiated some time between ~ 136 and 130 Ma (Gibbons et al., 2012; Robb et al., 2005), thus accentuating the inundation of the margin that is observed in the paleogeographic reconstruction.

Although the plate motion model is consistent with the rifting history between Australia-India-Antarctica, Golonka's (2007) plate motion model may need refinement for the Cretaceous Australia-Antarctica rifting history. The paleogeographic model suggests that inundation of the western Australia-Antarctic margin initiates by 125 Ma and propagates eastward, reaching Tasmania by 100 Ma, consistent with a previous onset of rifting in the Valanginian (Totterdell and Bradshaw, 2004). The progressive submergence of the margin reflects the eastward propagation of the rift, as originally suggested by Mutter et al. (1985), that may be accentuated by the global mid-Cretaceous seafloor spreading pulse resulting in a eustatic sea level highstand (Seton et al., 2009). However, the peak of the sea level highstand and seafloor spreading pulse post-dates the peak inundation of the rifted Australia-Antarctica margin, and suggests that the progressive inundation was mainly rift-related. The pre-breakup fit in the Golonka (2007) model requires refinement to minimise continental overlaps and initiation of rifting at ∼ 121 Ma as demonstrated by Williams et al. (2011) for the Australian-Antarctic conjugate margins.

The pre-breakup fit between Greater India and western Australia, and in particular the extent of Greater India, is another long-standing controversy that can be viewed in the context of paleogeography (Fig. 9). The proponents of a maximum-extent Greater India suggest that the limit of this margin extended to the northern Exmouth Plateau at pre-breakup fit (Lee and Lawver, 1995; van Hinsbergen et al., 2011), while alternative models propose a smaller Greater India bound by the present-day geometry of the Wallaby-Zenith Fracture Zone (Ali and Aitchison, 2005; Klootwijk and Conaghan, 1979; Replumaz et al., 2004; Zahirovic et al., 2012; Gibbons et al., 2012). Our plate reconstructions with combined biogeography and paleogeography indicate that inundation of the western Australian margin did not extend south of the Wallaby-Zenith Fracture Zone until the final breakup of India from Australia in the Cretaceous (Fig. 10). This suggests that the Greater Indian continental margin extended no more than ∼ 1000 km north of the present-day suture zone, and supports a small Greater India. Although it may be suggested that the inundation north of the Wallaby-Zenith Fracture Zone resulted from a thinned and submerged large Greater India, the north-westward detachment of terranes from NW Australia would have generated a narrow continental margin along northern Greater India along transforms similar in orientation to those in the Argo Abyssal Plain (Heine and Müller, 2005) and analogous to the narrow continental margin resulting from the shearing along the Romanche Fracture Zone and the Benue Trough between Ghana and Nigeria (Basile et al., 1993; Bonatti et al., 1994).

## 4.5 Data coverage and resolution

Data coverage of the eastern coast of Australia, follow the band of Cretaceous inundation, resulting in reasonable spatio-temporal coverage of the region (Figs. 5 and 10). At least five sizeable gaps in the temporal coverage are present in the paleobiology and we suggest that some of the temporal gaps are a result of the episodic orogenic events related to the Tasman Orogenic System in the Paleozoic, leading to the eastward growth of the Australian continent in an accretionary convergent margin setting (Coney et al., 1990; Crawford et al., 2003; Henderson et al., 2011; Solomon and Griffiths, 1972). The lack of fossil assemblages elsewhere in Australia is a result of biased sampling and the environment type at the time. The combination of paleobiology, plate reconstructions and the paleogeography in *GPlates* has allowed us to use a novel approach to test the correlation of existing paleogeographic maps and fossil indicators of environments. The use of *GPlates* is significant, as paleogeographic maps can be dynamic and updated with relative ease based on new data, rather than the reliance on static maps that are revised infrequently. *GPlates* also allows the incorporation of multiple layers of proxy data to increase the confidences of paleogeographic reconstructions. The development of such interactive maps can be applied to other areas of geodynamic modelling, due to the technological capabilities demonstrated by *GPlates*.

Spatio-temporal data coverage is a considerable concern in the interpretation of the fossil record since poor sampling is difficult to distinguish from lack of fossil preservation. Regions in the northern hemisphere, such as North America and Europe typically display a greater abundance of biogeographic data compared to areas in the present day southern hemisphere, such as Australia. Such discrepancies may be the result of biased sampling and/or preservation and environmental conditions at the time of deposition. Global data coverage is relatively poor for times before the Carboniferous; this may be attributed to the poor preservation of organisms. Spatio-temporal data coverage in Australia has predominantly been restricted to eastern Australia, and suggests at least five temporal gaps in coverage (Fig. 10). Paleogeographic reconstructions were further restricted by the lack of variation in fossil assemblage environments: paleobiology data are predominantly available for marine paleoenvironments. As a result, other proxy data are required for constraining paleoenvironments with low biological preservation potential – such as orogenic settings that can be constrained using metamorphic assemblages and denudation histories in proximal basins. Paleogeographic maps can be further refined by incorporating additional published paleoenvironment indicators, including well logs and other time-dependent datasets using *GPlates*. Future directions include a greater analysis of paleogeography on a global scale as indicated by biogeography, including the effect of glaciations, continental inundations and mass extinction throughout the Phanerzoic on fossil assemblages. In particular, such an approach would be best suited for European and North American paleogeographic reconstructions due to the higher spatio-temporal coverage in the fossil record (Hannisdal and Peters, 2011).

Glaciations have played a major role in global climate throughout the Phanerozoic, and may have influenced the preservation of organisms. The glaciation throughout the latest Devonian to Early Permian (Scotese et al., 1999) may be responsible for the few and scattered fossil assemblages found globally in the Late Paleozoic. Similarly, the inundation of continental regions can influence preservation of organisms, based on the availability of desirable preservation conditions, and should be noted in global and regional observations in plate reconstructions. Sudden increases in fossil abundance temporally and spatially may reflect local environmental changes and preservation conditions, rather than an increase in biodiversity or biologic density. Specifically, the inundation history of Australia, throughout the Cretaceous, is associated with increased spatial and temporal fossil preservation in the eastern Australian basins (Fig. 10). The increased inundation of the continent and a biased biological preservation during this time interval is consistent with a mid-Cretaceous seafloor spreading pulse and increase in eustatic sea levels (Seton et al., 2009).

## 5 Conclusions

Our approach demonstrates that paleogeographic and plate reconstructions can be improved and refined using biogeographic indicators from the global Paleobiology Database. Our novel application of spatio-temporal data mining can be used to identify inconsistencies between paleogeography and biogeography. Our approach allows the incorporation of multiple proxy datasets to help refine plate and paleogeographic reconstructions, and enables the creation of a new generation of digital and interactive models that allow users to create dynamic maps that are expandable and testable that take advantage of regularly maintained databases such as the global paleobiology. Sediments and related fossil assemblages are largely confined to basins and this only provides indirect constraints for elevated topographic regions representing sediment sources. As a result, in the future it will be desirable to incorporate proxies of elevation, such as paleo-altimetry estimates based on paleobiological indicators (i.e. leaf morphologies and stomata densities) (McElwain, 2004), and stable and metamorphic assemblages isotopes (Blisniuk and Stern, 2005). *GPlates* is evolving into an open innovation platform with a plugin infrastructure and an extended information model that will enable the creation of adaptable and interactive paleogeographic maps that are expandable in order to assimilate growing chronostratigraphic data systems (Sikora et al., 2006) in addition to paleobiology data.

**Supplementary material related to this article is available online at: http://www.biogeosciences-discuss.net/9/9603/2012/ bgd-9-9603-2012-supplement.zip.**

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**Table 1.** Paleogeographic descriptors in the Paleogeographic Atlas of Australia (Langford et al., 2001) and colour (RGB) values representing each environment.

| | Paleoenvironment | Descriptor | RGB Code |
|---|---|---|---|
| Marine | Bathyal-Abyssal and Abyssal | Deep water sediments including condensed sequences, turbidites and shales indicative of water depths exceeding 200 m. | 22/253/255 and 20/209/253 |
| | Shallow | Sediments deposited on continental shelves including sand, mud and limestone indicative of 20 to 200 m watch depths. | 159/255/255 |
| | Very Shallow | Sediments deposited above wave base including oolitic and cross-bedded deposits indicative of 0 to 20 m water depths. | 228/255/253 |
| | Coastal depositional deltaic | Protruding lobate outline of sedimentary extent. | 224/247/218 |
| | Coastal depositional paralic | Environments representing land-sea interface including lagoonal, estuarine, beach and intertidal sediments. Facies including cross-bedded beach sands and finely laminated organic sediments. | 224/247/142 |
| Coastal | Depositional fluvial | Alluvial river deposits of braided and meandering streams, dominated by sandy sediment and coarser sediment. | 255/239/163 |
| | Depositional fluvial-lacustrine | Low energy depositional environments of fine grain sediment (including coal) such as in river channels, swamps, floodplains and shallow lakes. | 234/201/162 |
| Land | Depositional erosional | Erosional regions with higher relief based on paleo-currents, volcanic activity and tectonic setting. | 237/185/174 |
| | Depositional unclassified | No preserved sediments of age representing paleogeographic reconstruction. | 248/243/237 |
| | Glacial | Sediments including glacial tillite and dropstones indicative of glacier movement and transport. | 255/207/237 |

**Fig. 1.** Plate reconstruction of Pangea at 250 Ma with reconstructed present-day topography and coastlines for reference. Continental overlaps indicate post-breakup extension of continental crust. Dashed lines indicate our relative plate motion hierarchy in the Paleozoic based on Golonka (2007), with Africa as reference plate that moves relative to the spin axis using rotations derived in *GPlates* software from the spherical spline option from the Geocentric Axial Dipole (GAD) reference frame in Torsvik and van der Voo (2002). Abbreviations: NC – North China, SC – South China, CIM – Cimmerian terranes, AUS – Australia.

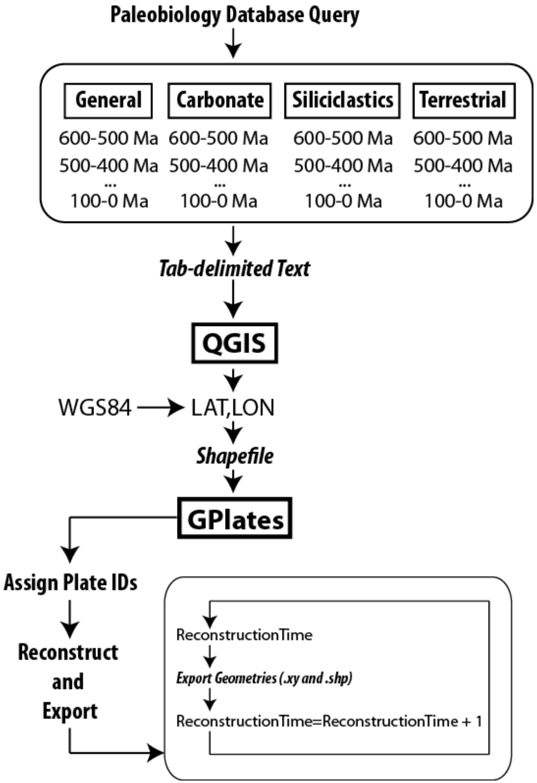

**Fig. 2.** Workflow of converting Paleobiology Database query results into *GPlates*-compatible files using *QGIS*. Continental Plate IDs are assigned to each fossil collection using continental block outlines, and the data is rotated in *GPlates* using our plate motion model for the Phanerozoic. Geometries were exported as simple ASCII and ESRI Shapefiles using the WGS 84 datum.

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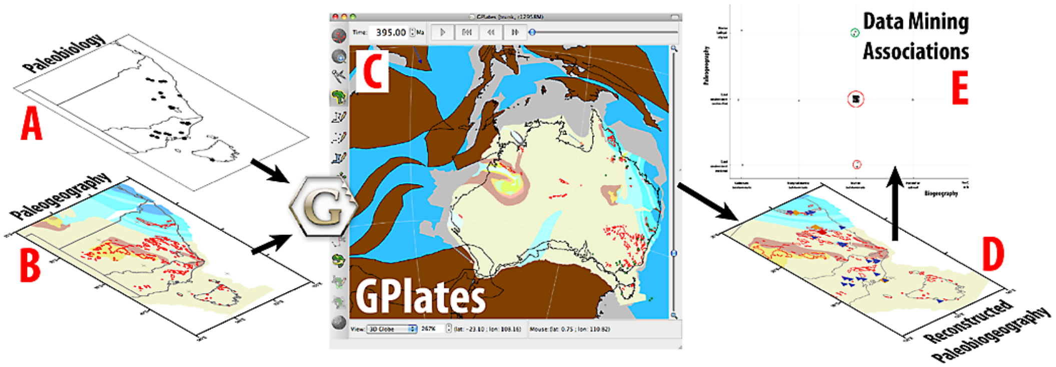

**Fig. 3.** Fossil collections **(A)** and the Australian paleogeography **(B)** are reconstructed in *GPlates* **(C)** using a Phanerozoic plate motion model, from which reconstructed paleogeographies **(D)** and data associations **(E)** are derived in order to test and refine the paleogeographic and plate motion model.

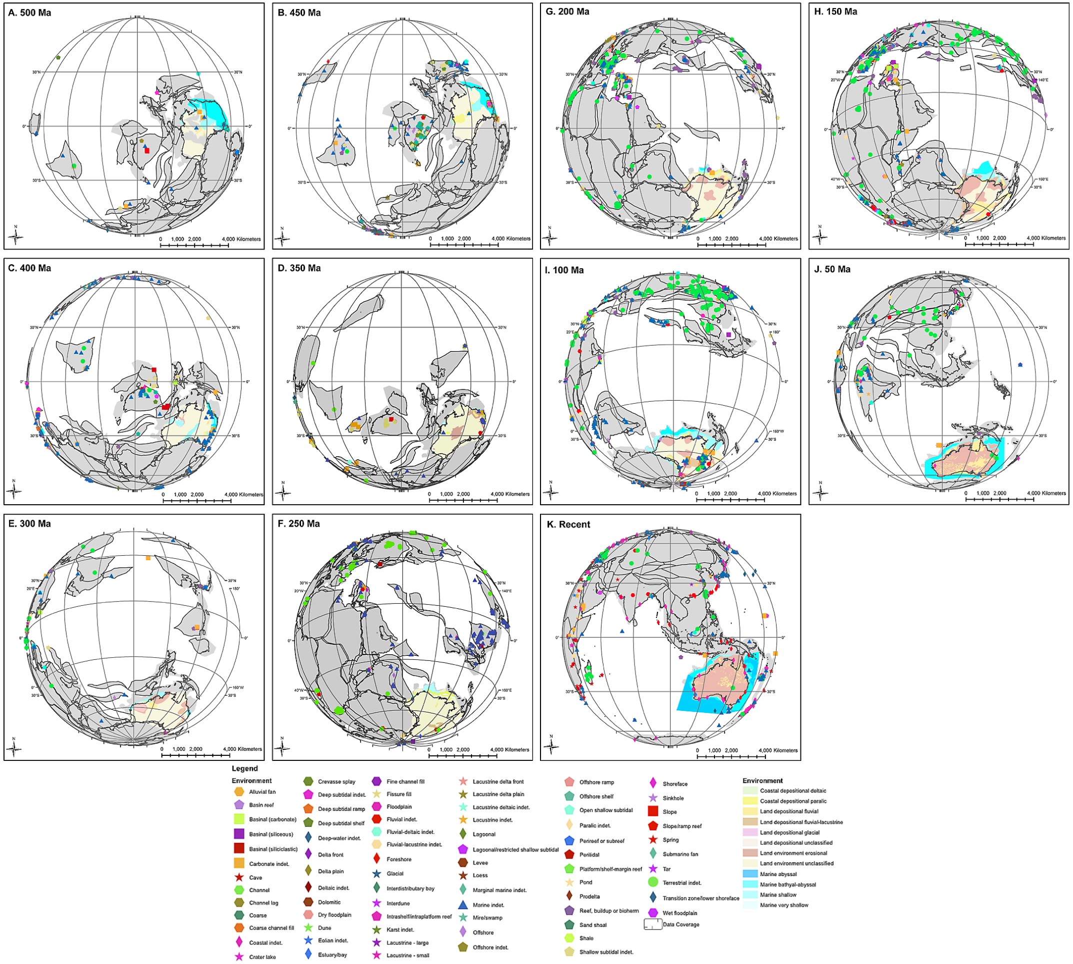

**Fig. 4.** Phanerozoic global plate reconstructions with Australian paleogeography and biogeographic indicators in 50 Myr increments. See coloured symbols (left) for depositional environments represented by biogeographic indicators from the paleobiology database, and coloured rectangles (right) depicting depositional environments reconstructed from a synthesis of geological data in the Geoscience Australia Paleogeographic Atlas.

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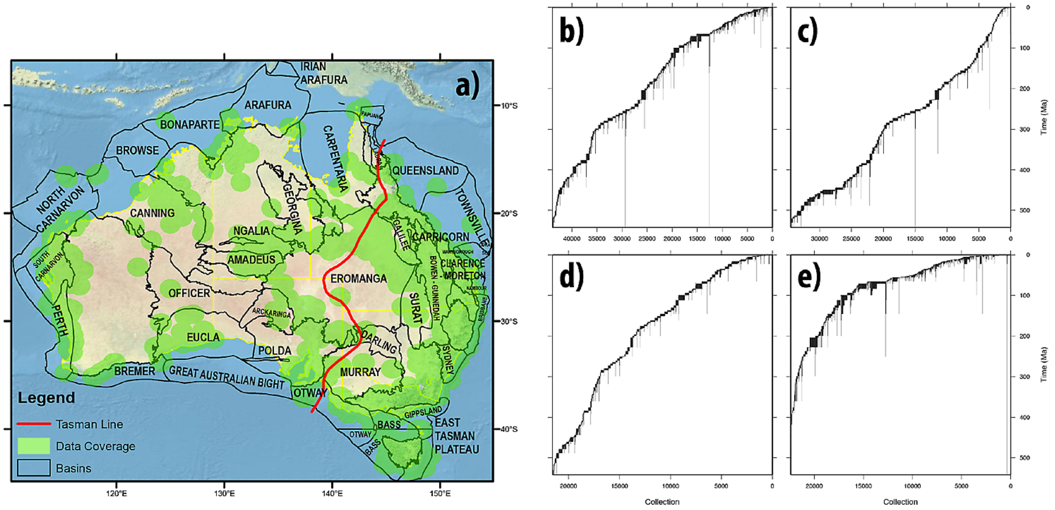

**Fig. 5. (a)** Data coverage with 100 km buffer (green) from the Paleobiology Database for Australia, with basin outlines and political boundaries as reference. Temporal coverages of fossil collections are for **(b)** general, **(c)** carbonate, **(d)** siliciclastic marine, and **(e)** terrestrial fossil collections showing that the dataset sufficiently represents Phanerozoic biogeography.

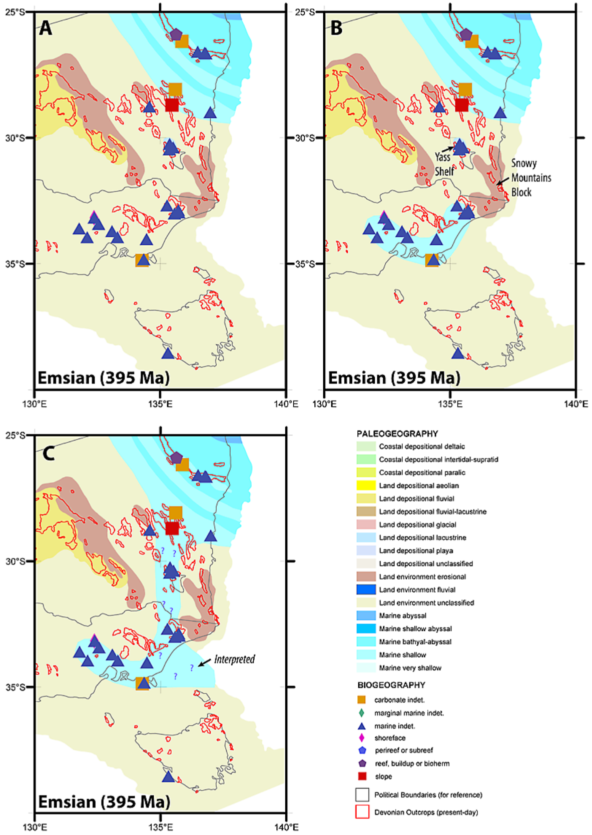

**Fig. 6.** **(A)** Paleogeographic reconstruction at 395 Ma (Early Devonian/Emsian) from Geoscience Australia Paleogeographic Atlas with biogeographic indicators, Devonian rock outcrops and reconstructed political boundaries for reference. Fossil specimens (including echinoderms, shell and skeletal fragments) in NSW and VIC indicate shallow marine environments. The fossils have well-constrained temporal descriptors indicative of Early Devonian times, with a number of specimens better tied to Emsian times based on conodont zones (i.e. *Eognathodus trilinearis*, *Polygnathus dehicens*, etc.). **(B)** A conservative reinterpretation of Emsian paleogeography of Victoria suggesting marine environments persisted until at least Emsian times, while **(C)** is an alternative interpretation that links the marine inundation to the Yass Shelf to be more consistent with the interpretations of Webby (1972) and the overall N-S striking convergent margin of Australia at this time.

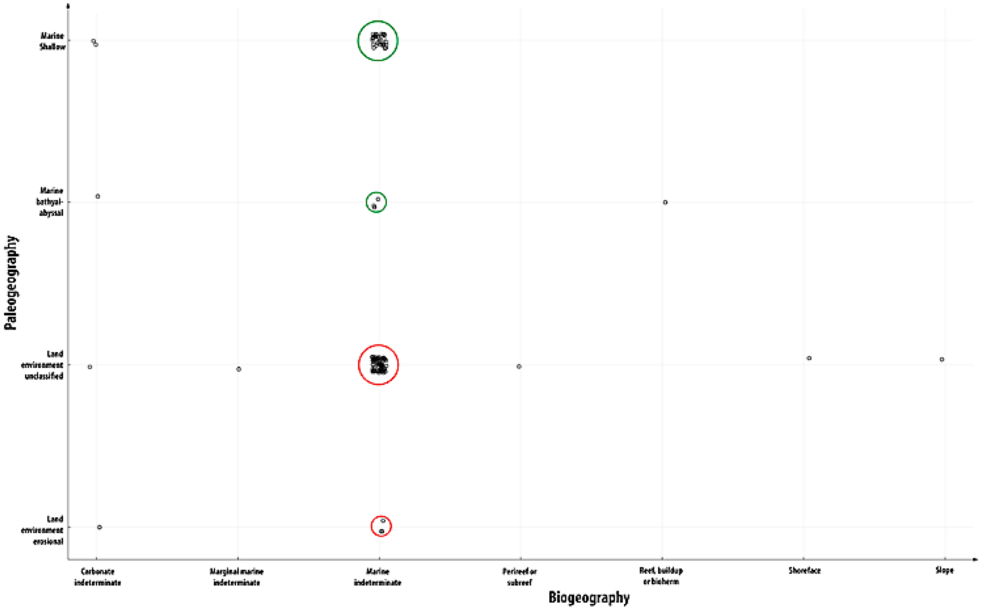

**Fig. 7.** Biogeographic and paleogeographic associations at 395 Ma (Early Devonian, Emsian times) highlight the discordance between the marine setting indicated by the fossil collections (green circles) and the Australian paleogeography at this time (red circles). The fossil collections, as the seed points, were used to extract the paleogeography to create a time-series for the purposes of data mining.

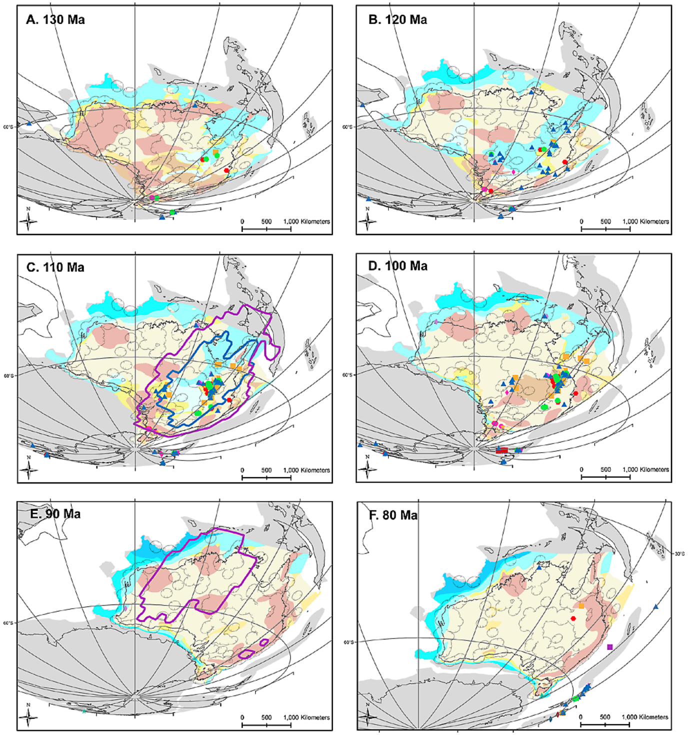

**Fig. 8.** Paleogeographic reconstructions suggest that Cretaceous inundation of central eastern Australia peaked by ~120 Ma, and the biogeographic indicators hint at pockets of shallow marine environments persisting beyond 100 Ma. The eastward sweeping negative dynamic topography system from a sinking Pacific-derived slab has been linked to the inundation pattern, better modelled by Model C (blue) than Model B (purple) in the geodynamic modelling results of Gurnis et al. (1998), highlighting how paleogeography can be used to validate numerical model predictions of basin evolution.

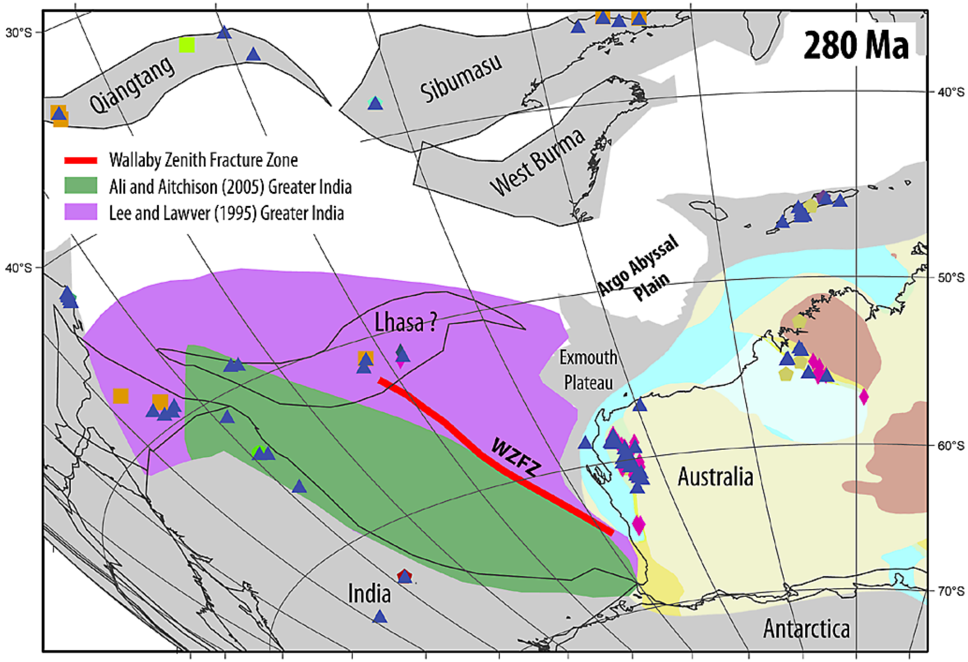

**Fig. 9.** Inundation history from the paleogeography and biogeography along the western Australian margin does not support a maximum extent Greater India (purple) as the inundation is confined to areas north of the present-day Wallaby-Zenith Fracture Zone (red), suggesting that a smaller extent of Greater India (green) is more likely.

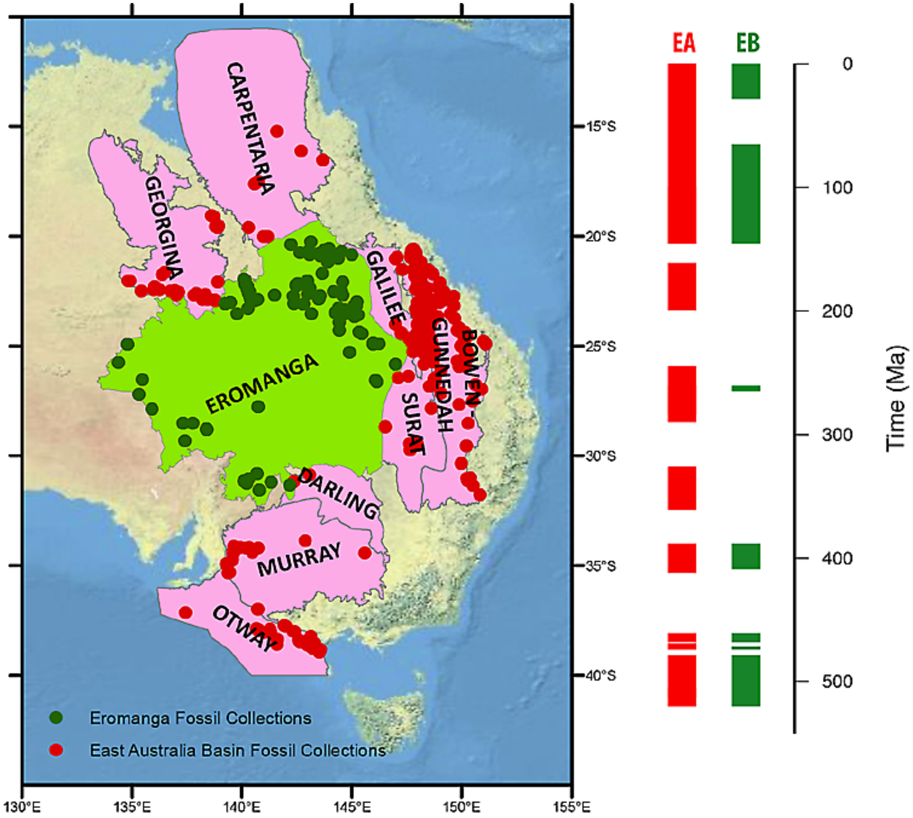

**Fig. 10.** Temporal coverage of Eastern Australian basins (EA) and the Eromanga Basin (EB). Much of the sampled collections are on the outskirts of the Eromanga Basin with data gaps that may be related to sampling gaps, orogenic episodes and the influence of glaciations on Eastern Australia during the Late Paleozoic.