Modelling and visualising distributed crustal deformation of Australia and Zealandia using GPlates 2.0

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SUMMARY

The recently released GPlates 2.0 software (www.gplates.org) provides a framework for building plate motion models including distributed extension and compression, driven by the motions of the surrounding rigid plate interiors, with constraints assimilated from well and seismic data. Here we present a regional deforming plate model for Australia and Zealandia. It captures the progressive extension of all Australian continental margins, starting with the Jurassic extension of the northwest shelf, and the Cretaceous extension of the southern and eastern Australian margins. The model also includes the extension of the Lord Howe Rise and southern Zealandia in the mid- to Late Cretaceous and the subsequent complex compressional deformation of New Zealand since the early Miocene. The model enables the time-dependent computation of crustal stretching factors for passive margins, as well as compression factors for orogenic regions. The thinning/thickening can be tracked by points distributed within a deforming mesh, either by starting with an assumed initial stretching factor or by applying an iterative approach in estimating initial crustal thicknesses to account for present-day constraints. The latter is suitable for basins, while the former is more applicable for orogens, where the present-day crustal thickness is not a reliable indicator of total crustal thickening due to the effects of erosion. Modelled crustal stretching factors can also be ground-truthed with independently derived stretching factors from strain rate inversion of stratigraphic sequences from well data or forward models of tectonic subsidence. The model can be combined with estimates of mantle-driven dynamic topography through time to generate basement subsidence or uplift models that include isostatic and dynamic components, serving as boundary conditions for basin and source-to-sink sediment transport models to provide improved constraints for resource exploration.

Key words: Rift systems, plate tectonics, basin modelling, Australia, Zealandia

INTRODUCTION

GPlates is an open-source and cross-platform paleo-geographic information system that enables geoscientists to combine a wide variety of geodata and examine them within a deep-time plate tectonic reconstruction context. The most recent version, GPlates 2.0, contains significant new capabilities, in particular the introduction of deforming plate functionality. This major advance allows users to define plate deformation zones. These are regions combining extension, compression and shearing that accommodate the relative motion between rigid blocks that follow more traditional concepts of plate tectonics. Users can explore how strain rates, stretching/shortening factors and crustal thickness evolve through space and time within deforming regions, and interactively update the kinematics associated with deformation to see how these parameters are influenced by alternative scenarios. The geometries that define regions of deformation change over time in response to the user-defined kinematics, and the consequences of these changes can be quantified and represented using stretching/shortening factors. Together, the new tools form the basis for building reconstructions that quantitatively describe the cycles of rifting, mountain building, and intra-continental shearing that accompany supercontinent assembly and dispersal. The primary purpose of this contribution is to illustrate the deforming plates methodology, and for this purpose we apply this method to build a model that represents the major extensional and compressional deformation around Australia's margins and within Zealandia since the late Jurassic. In some regions the existing reconstruction shows a good agreement with available data, while other regions highlight where more data are needed to constrain the spatio-temporal evolution of deformation.

METHOD AND RESULTS

A complete description of the deforming plate methodology is presented by Gurnis et al (submitted), which builds upon the concept of continuously closing plate models described by Gurnis et al (2012) and used to construct the latest generation of global plate tectonic reconstructions (Müller et al, 2016). Each of these methods is also extensively outlined in the GPlates online documentation (www.gplates.org). Here we provide a brief summary of the key points in generating reconstructions that model lithospheric deformation.

The building blocks of a deforming plate reconstruction are points, lines and polygons that define plate boundaries, the boundaries between deforming and rigid regions, and can partition the deformation with the regions of deformation. Each of these geometries can be assigned its own history of motion in the same way as a plate. The GPlates user interface is designed to facilitate the process of defining both the extent of deforming regions and the motion history of each building block. The spatial extent of deforming meshes is mainly based on a variety of geological and geophysical evidence - for example, grids of crustal thickness, grids of sediment thickness for extensional regions, and the topography and structure of mountain belts here focussed on the Southern Alps. We assimilate these observations into the model of plate motions within our reconstructions, and compute time-dependent stretching or compression within deforming regions based on the kinematic motions of the surrounding (rigid) features. In the case of passive margins, we also model the end of extensional deformation to coincide with the timing of the onset of seafloor spreading.

To infer stretching factors, an assumption of the crustal thickness prior to a given phase of extension must be made - this is simple to modify within the GPlates interface, allowing multiple estimates of stretching factor be determined for a single kinematic reconstruction based on alternative pre-rift scenarios. A simplification in the current model is the absence of deformation partitioning within each margin, so there is currently no distinction between high extension factors expected in distal margin areas versus the more moderate amounts of extension closer to the rift edge - instead, the displayed values represent average stretching factors for each margin segment that vary along strike. Finally, the reconstruction here is limited to the time between 160 Ma and present day. While this time period captures the majority of rifting that has shaped Australia's margins during Gondwana breakup, much of the extension on Australia's northwest shelf predates this period as outlined below. Thus, the stretching factors for the northwest shelf only capture the final stages of extension and are not intended to indicate the total stretching required to create the presently observed crustal thickness and subsidence histories in this area, which would of course be much greater. With these caveats in mind, we outline how deformation of individual regions has been constrained and modelled.

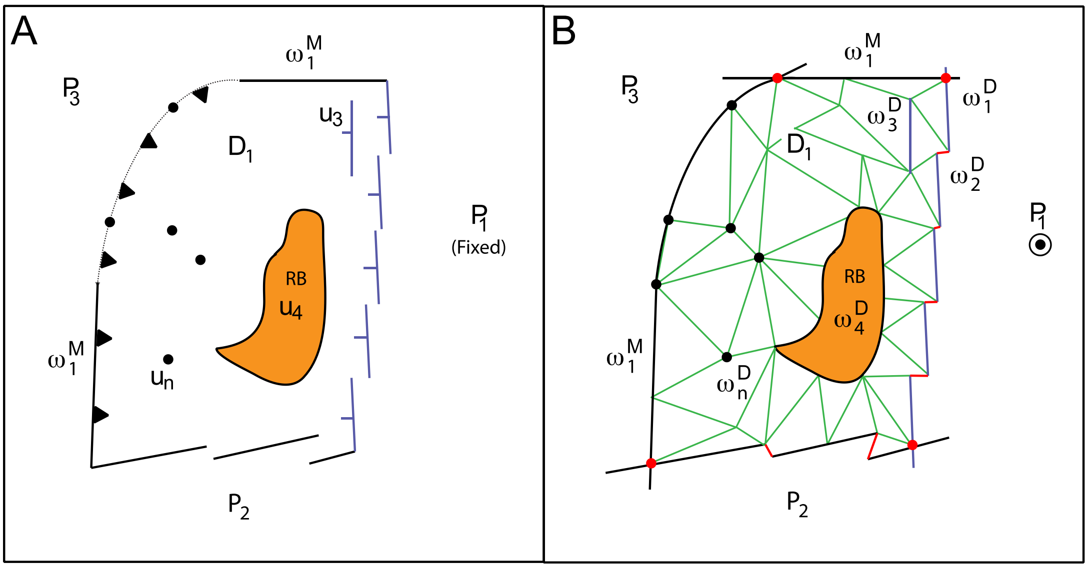

Figure 1. *Illustration of concepts used in building deforming plate reconstructions within GPlates 2.0 (after Gurnis et al, submitted). Individually feature geometries (points, lines and polygons) with distinct motion histories are defined by the user, as shown in panel A. These features are combined to define the extent of deformation regions and the partitioning of strain within the region (panel B). The velocities and strain histories of additional points within the deforming region is (shown by the triangulation) is computed by interpolation.*

Jurassic extension along Papua New Guinea

During the Jurassic, Papua New Guinea underwent crustal thinning due to the rifting of the Sepik continental block (Fig 2a). We defined the boundaries of the rifting region to lie west of the Tasman Line and north of the Mapenduma fault as proposed by Hill and Hall (2003). The rifting was caused by slab rollback brought about by the south-dipping subduction zone (Zahirovic et al., 2016). Based on evidence from supra-subduction zone ophiolites in the Central Ophiolite Belt, the Sepik continental block entirely separates from the Papua New Guinea mainland by ~155 Ma marking the end of the continental extension (Permana, 1998). The style of rifting and break-up results from the underlying crustal architecture, the structural grain found in the northeast of Papua New Guinea produces the localities of extended continental crust separated by embayments of Jurassic oceanic crust (Hill and Hall, 2003). In the extended promontories, our model predicts stretching factors of up to 1.7.

Jurassic Northwest shelf extension

There is a long history of episodic rifting, including failed and reactivated rifts, along the northwest shelf of Australia (Longley et al, 2002; Dore and Stewart, 2002). These rift episodes date back to the Paleozoic, but for our simplified model we include only the final deformation phase that postdates 160 Ma. In this final stage of extension the northwest shelf experienced a transition from rifting to seafloor spreading in the Late Jurassic with the separation of the Argoland continental fragment; this is well established based on magnetic anomaly interpretations for the Argo Abyssal Plain, off NW Australia, the oldest one of which is ~M25 (155 Ma). Our model describing Jurassic rifting, breakup and passive margin formation along the Northwest shelf follows the model of Gibbons et al. (2013) and which invokes continental block detachment in the Argo Abyssal Plain at ∼155 Ma, roughly contemporaneously with breakup further east along the northern Australian margin. The model corresponds to a pre-rift scenario along northern Gondwana with rifting associated with a triple junction detaching the East Java, West Sulawesi, East Borneo and Mangkalihat terranes from the northwest shelf driven by north-dipping subduction along the Woyla intra-oceanic arc (Zahirovic et al., 2016). Our very schematic model exhibits low average stretching factors of 1.07 for the post-160 Ma rifting, somewhat lower than Jurassic stretching factors for the region estimated from well data, for instance averaging ~1.2 in the Bedout Sub-Basin (Müller et al., 2005), 1.2 to 1.55 in the Vulcan sub-basin (Baxter et al, 1999), and values for lithospheric stretching exceeding 2.5 around the Exmouth Plateau (Karner and Driscoll, 1999). Significant uncertainties in the present reconstructions relate to the absence of conjugate passive margin crust preserved intact and undeformed, and over exactly where to reconstruct rifted microblocks along the northern margin of Gondwana. The wealth of data available for the northwest shelf itself should allow a detailed model for the pre-160 Ma deformation within basins preserved on the Australian margin to be constructed that may cast new light on these controversies.

Cretaceous extension, western margin of Australia

The Western margin of Australia records rifting between Australia and Greater India from the Jurassic to the Early Cretaceous (Gibbons et al., 2013). North of the Perth Basin, much of the crust north of the Wallaby Zenith Fracture Zone is thought to be continent in nature, this helping to constrain represents the northern limit of Greater India within Gondwana (Ali and Aitchison, 2014). The model presented here for eastern Gondwana breakup is simplified from the plate kinematic model of Gibbons et al. (2013), with only the main blocks (Australia, Greater India, and Argoland) represented, and several ridge jumps are omitted. Recent advances to our knowledge on the rifting and seafloor spreading history in the Perth Basin demonstrate the formation of microcontinents conjugate to the Perth Basin (Whittaker et al, 2016), but these events are not yet incorporated into the reconstruction presented here. The extension within the Perth Basin leads to seafloor spreading in the Perth Abyssal Plain from around 130 Ma (Williams et al, 2013), but a continental connection between Australia and Greater India across the Wallaby Zenith Fracture Zone likely persisted towards the middle of the Cretaceous (Fig 2b). As with the northwest shelf, any attempt to determine stretching factors from a reconstruction model in this area is limited by the lack of a well-preserved conjugate margin and the stretching factors illustrated within Greater India are somewhat arbitrary.

Cretaceous-Cenozoic extension of southern Australian margin

Rifting between Australia and Antarctica began during the Late Jurassic and ultimately led to the separation of Antarctica from Australia (Norvick and Smith, 2001). Previous studies have recognised the crucial importance of restoring large amounts of continental extension when reconstructing the rift history (e.g. Powell et al, 1988), and large stretching factors are necessary to explain the development of hyperextended crust presently found in the Bight Basin (Direen et al, 2012; Blevin and Cathro, 2007). Our model describing rifting, breakup and passive margin of the southern Australian margin follows the model of Williams et al. (2011, 2012). The boundaries of the continental deformation were derived from seismic, potential field, and geological data and the restoration of the continents to their most likely configuration prior to rifting was derived by integrating crustal thickness estimates (Kuzsnir, 2009) along tectonic flow lines. In the reconstruction, deformation begins at ~160 Ma but with relatively slow extension rates. An acceleration in rift velocity in the late Cretaceous (around 100 Ma, Fig 2c) is required to satisfy constraints from the Kerguelen-Broken Ridge sector of the Australia-Antarctica plate boundary system (Whittaker et al, 2013), and leads to diachronous breakup beginning first in the west and progressing eastwards during the Late Cretaceous (Williams et al., 2012), with sinistral transtension in the Otway and Sorell Basins (Norvick and Smith, 2001). Our model suggests variations in the magnitude of extension, with stretching factors lower in the west and higher towards the east along the margin. The overall magnitudes of extension and average stretching factors, in the range 1.5 to 3, show good agreement with independently estimated stretching factors along Australia's southern margin Veevers, 2012; Espurt et al, 2012; (Kharazizadeh et al., 2016). Along-strike variations in deformation can be attributed to both the varying rift kinematics and the influence of rheological variations in the pre-existing basement, such as at the boundary between the Lachlan and Delamerian Fold Belts (Miller et al., 2002). A future improvement to the model would be to implement a more detailed history of strain distribution through space and time, such as the focussing of rifting into narrow distal regions during the late Cretaceous (Ball et al, 2013).

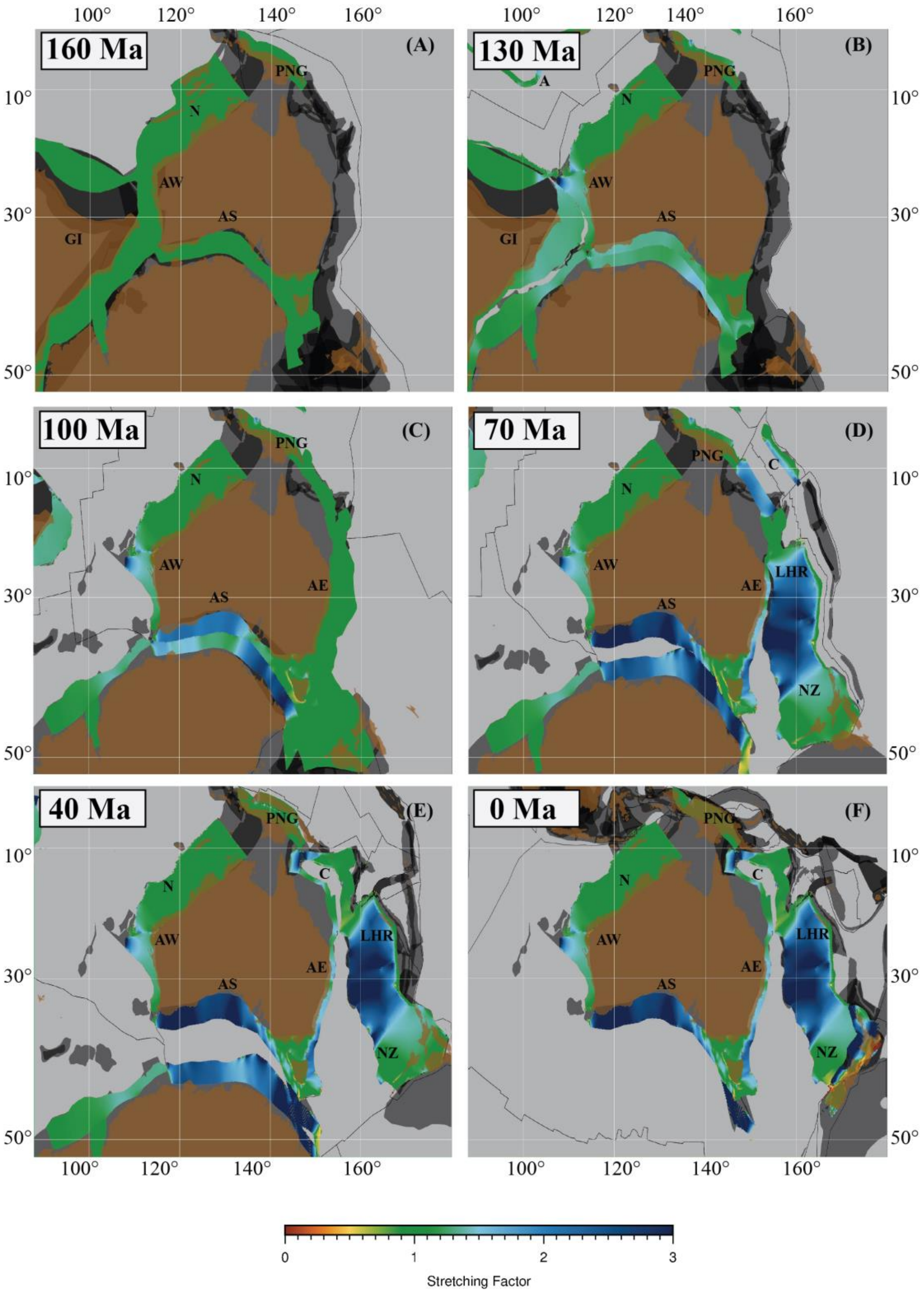

Figure 2. *Change in stretching factor modelled through time (Australian Plate fixed), from 160 Ma (a) to Present day (f). Abbreviations: A, Argoland; AE, Australian Eastern Margin; AW, Australian Western Margin; C, Coral Sea Basin; LHR, Lord Howe Rise; N, Northwest Shelf; NZ, New Zealand; PNG, Papua New Guinea. Dark grey areas represent continental-oceanic boundaries. Light grey areas represent oceanic crust. Black lines represent plate boundaries. The reconstruction was implemented using GPlates software available at http://www.gplates.org/*

Cretaceous-Cenozoic extension between Australia and the Lord Howe Rise

The major rifting event to have shaped the eastern margin of Australia is the Cretaceous rifting between Australia and Zealandia, which eventually resulted in the opening of the Tasman Sea. Prior to this rifting, the basement rocks of Zealandia are thought to have formed part of a cordillera that spanned much of the eastern Gondwana active margin (e.g. Norvick et al, 2008). A major unknown is the appropriate 'average' crustal thickness to ascribe to this crust before rifting starts - maximum crustal thicknesses may have reached 80 km (Milan et al, 2017) in parts of Zealandia south of the Lord Howe Rise, but present-day cordilleran systems show significant along-strike variation in thickness. The reconstruction used here is outlined in Müller et al. (2016). The extension in our model begins around 100 Ma, possibly linked to changes in absolute plate motion and subduction dynamics at the Gondwana margin (Rey and Müller, 2010; Collot et al, 2009). The fragmentation of the previous active margin lead to seafloor spreading that is documented in Gaina et al. (1998) based on magnetic anomaly identifications and fracture zones derived from gravity anomalies. Breakup starts earliest in the south and becomes progressively later to the north. Magnetic, seismic and gravity data indicate that the entire continental fragment experienced stretching, but to varying degrees (Segev et al., 2012; Norvick et al, 2008) with major depocentres separated by regions of more moderately thinned crust (Higgins et al, 2015).

Cenozoic Coral Sea region extension

The Coral Sea is located off the north-eastern coast of Australia between the Papuan Peninsula and Louisiade Plateau in the north and the Queensland Plateau in the south (Fig 2d-e). There were three main rifting events in the Coral Sea region; the model focuses on the most recent extensional phase which terminated with breakup and the onset of seafloor spreading at 63 Ma, propagating westward until it ceased at 52 Ma (Gaina et al., 1999). An older rifting event starting around 90 Ma has been incorporated in the model reflecting the regional polyphase extension history (Bulois et al., 2017). The opening of the Coral Sea at 63 Ma has a well-documented tectonic history (Gaina et al., 1999). The northern boundaries of the deforming region were constrained to the Osprey Embayment, Papuan Plateau, Eastern Plateau, Southern Papua New Guinea and Louisiade Plateau. We inferred the boundaries of our deforming model from satellite gravity and bathymetry, and the CRUST 2.0 global structure model (Gaina et al., 1999, Segev et al., 2012, Laske et al., 2000). The Queensland and Marion plateaus constrain the southernmost extent of the deformation in our model (Weissel and Watts, 1979); present-day Moho depths were also used to constrain appropriate boundaries for the extent of deformation (Salmon et al., 2012). The constraints available to quantitatively model plate motions and plate deformation around northeast Australia are particularly sparse, suggesting that this should be a focus area for future marine geoscience expeditions.

Cenozoic Oblique compression in New Zealand

The land areas that form New Zealand are part of the vast submerged continent Zealandia (Mortimer et al., 2015), which is composed of the Challenger Plateau-Lord Howe Rise, Chatham Rise, and Campbell Plateau. Geological evidence indicates that New Zealand underwent large-scale deformation during the Cenozoic (Wood and Stagpoole, 2007). Our model for deformation from 40 Ma to present (Fig 2e-f) is based on the model by Wood and Stagpoole (2007), which incorporates a detailed description of plate kinematics, interpreted paleogeography and balancing of erosion and sedimentation within New Zealand's continental landmasses. The reconstruction provides a more detailed representation of deformation than previous global reconstructions (e.g. Müller et al, 2016), with individual motions defined for the blocks corresponding to the Western North Island, East coast North Island, Marlborough, west coast South Island, and east coast South Island Fjordland (Wood and Stagpoole, 2007). The resulting pattern of deformation includes regions of extension, shortening and highly oblique tectonics during the Eocene. Oblique compression along the Alpine Fault formed the Southern Alps, the North Island's eastern ranges and the East Coast fold and thrust belt (Wood and Stagpoole, 2007). In contrast, south-eastern regions of the Hikurangi and Campbell plateaus underwent significant extension. After 20 Ma, eastward trench retreat occurred due to the rotation of the Hikurangi margin (Lamb, 2011) - this rotation may indicate that the continental lithosphere is relatively weak allowing boundary forces to govern deformation, and causing deformation to passively follow the change in the trend of the subduction zone through time (Lamb, 2011). The model presented here does not in itself offer new insights into the deformation of this region - rather, it serves as an illustration of how GPlates deformation tools can be used as a framework to build such reconstructions both as standalone regional models, and embedded with a self-consistent global reconstruction.

DISCUSSION AND CONCLUSIONS

Despite the simplifications outlined earlier, the preliminary reconstruction here is nonetheless a useful illustration of how the tools available within GPlates 2.0 can be used to test different scenarios, revealing the success of otherwise of existing reconstructions in producing estimates of deformation that are consistent with observations. For example, our reconstruction of Australia's southern margin produces stretching factors that agree favourably with values derived from various analyses of seismic data. Alternative models arguing for a much looser fit prior to rifting are inconsistent with these observations, a conclusion that hold regardless of what initial crustal thickness is assumed. For Zealandia, the thickness of the crust prior to the onset of extension in the mid-Cretaceous is much less certain, and while our resulting stretching factors for sections of the Lord Howe Rise suggest that 40 km may be a reasonable value, other scenarios cannot be excluded. Either the prescribed motion history or the assumed pre-rift crustal thickness (and how it may have varied spatially) can be modified in order to explore alternative histories that could explain the observed extension between the eastern margin of Zealandia and rigid Australia prior. This parameter exploration can be carried out iteratively and interactively within the GPlates GUI.

Incorporating deformation produced by tectonics is crucial for deriving accurate full-fit reconstructions and provides a more realistic approach than applied in rigid plate motion models. The methodology summarised here illustrates how the consequences of quantitative reconstructions can be visualised and modified through time. As well as illustrating a workflow towards generating more robust reconstructions, our continent-wide deforming plate model provides boundary conditions for modelling of the geodynamic processes influencing sedimentary basin through time. Using GPlates to generate models that track changes in crustal thickness through time, we can assess the influence of tectonics on vertical motions of the Earth's surface on geological timescales in the context of other processes such as flexure and dynamic topography (Flament et al, 2014). Coupling time-varying topography with surface process models (e.g. Salles et al, 2017) provides a new avenue to quantitatively model the erosion and deposition of sediments through time in complex tectonic regions.

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