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***Author for correspondence:**
Alexander L. Peace,
Email: peacea2@mcmaster.ca

Beyond 'crumple zones': recent advances, applications and future directions in deformable plate tectonic modelling

Alexander L Peace

School of Earth, Environment and Society, McMaster University, Hamilton, ON, Canada

Abstract

The recent proliferation of deformable plate tectonic modelling techniques has provided a new direction in the study of plate tectonics with substantial implications for our understanding of plate deformation and past kinematics. Such models account for intraplate deformation, yet are highly variable in their inputs, capabilities and applications. The aim of this commentary is to review recent contributions to this topic, and to consider future directions and major omissions. Through this review it is apparent that the current published deformable models can be subdivided into those that as an input either: (1) solely use plate motions to drive deformation, or (2) require stretching or beta factor. Deformable models are resolving some outstanding issues with plate reconstructions, but major simplifications and modelling assumptions remain. Primarily, obtaining model constraints on the spatio-temporal evolution of deformation is an outstanding problem. Deformable plate models likely work best when the kinematics of smaller plates are included. However, questions remain regarding how to define such blocks, and their kinematic histories, whilst some work suggests that inclusion of such entities is negated through quantitative restorations.

1. Introduction

Plate tectonics describes the movement of a number of rigid bodies making up the Earth's exterior with respect to one another (McKenzie & Parker, 1967; Morgan, 1968). These movements can be described by the rotation about a fixed point, the Euler pole, forming the basis of the kinematic description of plate tectonics (Greiner, 1999). Euler pole rotations of rigid plates on a sphere can be used as the basis to perform palaeogeographic reconstructions and to compare palaeomagnetic data from different continents (Greiner, 1999; Scotese, 2009). Since the advent, and development, of plate tectonic theory, numerous plate tectonic models have been developed (Seton *et al.* 2012; Matthews *et al.* 2016; Vérard, 2019). Each of these models, however, comes with its own assumptions and simplifications depending on the data used to construct the model, and also the purpose of the model (Peace *et al.* 2019).

Despite the proliferation of such models, plates, however, are clearly not rigid (Voight, 1974; Lobkovsky, 2016; Mazzotti & Gueydan, 2018). Space geodesy facilitated Gordon and Stein (1992) to build a present-day deforming plate model which estimated that *c.* 15 % of Earth's surface area today is deforming along diffuse deformation zones, which was later revised to 14 % (Kreemer *et al.* 2014). These observations confirm the necessity of accounting for intraplate deformation in plate reconstructions (Gurnis *et al.* 2018). Deformable plate models extend the concept of intraplate deformation from present-day observations (e.g. Mazzotti and Adams, 2005) by accounting for intraplate deformation through geological time (Müller *et al.* 2019). Thus, the definition of a plate tectonic model by Vérard (2019) can be extended to define deformable plate models as any tool, or reconstruction of the past positions and kinematics of continents, that allows for internal deformation of the plates. Unless deformation is adequately accounted for when past locations of the continents are reconstructed, under- and overfit is a prevalent problem (Zatman *et al.* 2001, 2005; Ady & Whittaker, 2019; Müller *et al.* 2019; Fig. 1). Yet, accounting for this deformation, constraining its timing (Stephenson *et al.* 2020) and realistically modelling and reconstructing it (Müller *et al.* 2019) represents an ongoing challenge in the development of realistic and useful plate models (Ady & Whittaker, 2019).

Irrespective of these challenges, the usefulness and applicability of such models for exploration on continental margins, and also for palaeogeographic, palaeooceanographic and palaeoclimatic modeling, is widely recognized (Ady & Whittaker, 2019). The motivation for building a plate motion model with distributed deformation includes understanding the evolution of orogens and sedimentary basins: for example, quantifying stretching or compression factors and crustal thickness changes through time (Müller *et al.* 2019). In addition, some of the limitations of current plate tectonic models, and in particular those

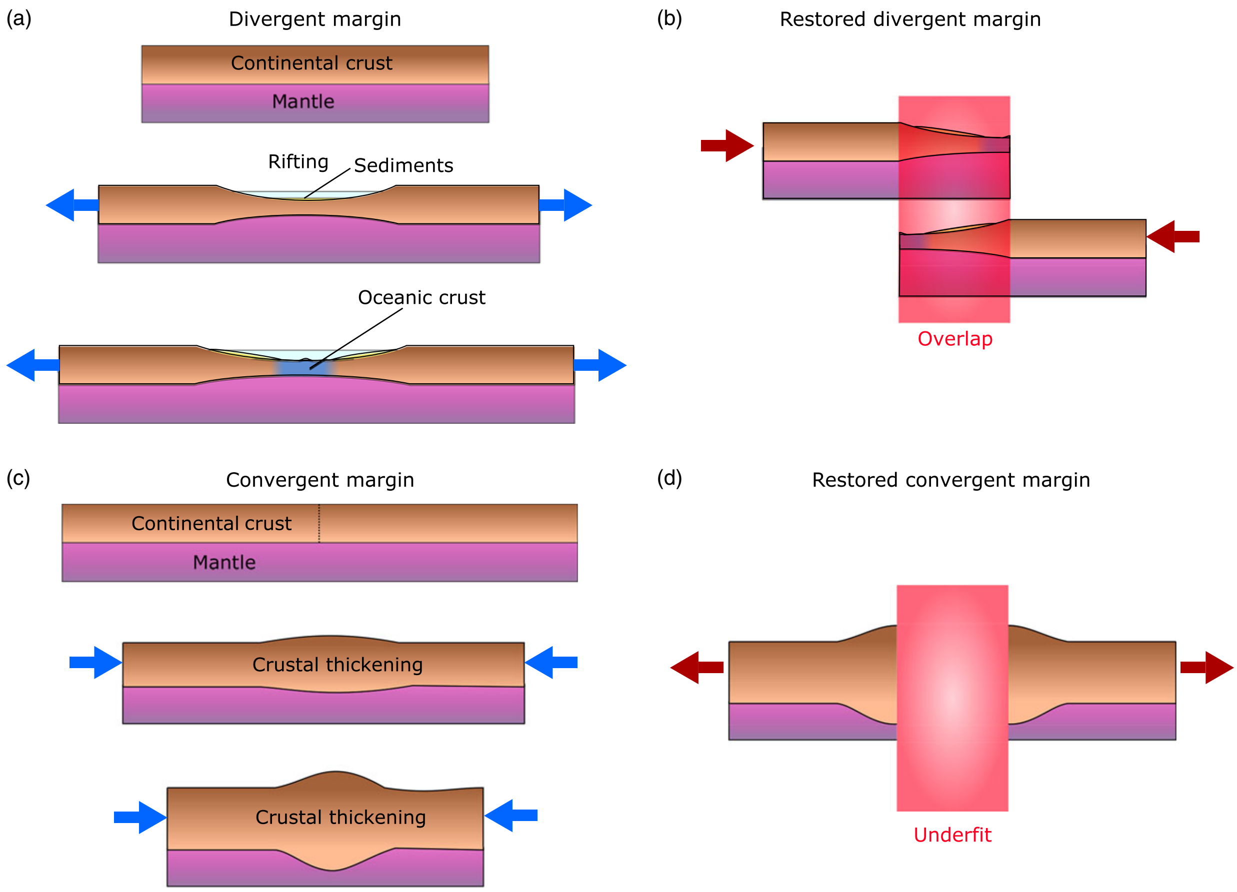

Fig. 1. (Colour online) Comparison of plate tectonic restoration at divergent and convergent margins following the concepts outlined and depicted in Ady & Whittaker (2019). (a) Progressive evolution of a divergent margin pair followed by (b) restoration of a divergent margin pair demonstrating the common overlap issue. (c) Progressive evolution of a convergent margin followed by (d) restoration of a convergent margin demonstrating the underfit issue.

that do not account for deformation, are becoming apparent (Peace & Welford, 2020). For example, in extensional tectonic settings they may lead to problems in reconstructing conjugate margins (Peace & Welford, 2020), and similar issues remain in reconstructing other tectonic environments (Gion *et al.* 2017). The aims of the present commentary are to: (1) review recent contributions to deformable plate modelling, at both the global and regional scales, and (2) consider the required future directions plus major omissions from models.

2. Deformable plate modelling methods and approaches

Rigid plate models can result in overlap at restored divergent margins, and underfit at restored convergent margins (Fig. 1, after Ady & Whittaker, 2019). To account for the internal deformation of plates, a variety of deformable plate modelling approaches have been developed. Recent works have provided highly insightful, yet variable, deformable plate models for a variety of tectonic settings (e.g. Cao *et al.* 2020). However, this is not an entirely new approach and Dunbar and Sawyer (1987) were among the first to attempt a quantitative approach to deriving non-rigid plate reconstructions, followed by others (Srivastava & Verhoef, 1992; Williams *et al.* 2011). A summary of the history of deformable plate modelling is provided in Ady & Whittaker (2019). A recent advancement has been the inclusion of this approach in open source software such as GPlates (Gurnis *et al.* 2018; Müller *et al.* 2018), resulting in deformable plate models of many regions (e.g. Cao *et al.* 2020) as well as globally (Müller *et al.* 2019). In addition, other groups have also developed their own deformable modelling workflows (Smith *et al.* 2007; Kneller *et al.* 2012, 2013; Ady & Whittaker, 2019).

One of the most prevalent of the deformable plate modelling workflows is that of the Earthbyte Group that is built into the GPlates software (after version 2.0) described in Gurnis *et al.* (2018) (Fig. 2). As a platform GPlates has been used extensively to produce both global (Matthews *et al.* 2016) and regional (Phethean *et al.* 2016; Gac *et al.* 2020; Romagny *et al.* 2020) rigid-plate models, as well as deformable ones (e.g. Peace *et al.* 2019; King *et al.* 2020). When constructing deformable models in GPlates, the geometry and time-constrained existence (time of appearance plus disappearance) of plate deformation zones between portions of the plates considered rigid is defined (Gurnis *et al.* 2018). The deforming regions combine extension, compression and shearing that accommodate the relative motion between rigid blocks (Gurnis *et al.* 2018). This allows users to explore how strain rates, stretching and 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 (Müller *et al.* 2019). It could be argued that the main limitation of the GPlates deformable models is that deformation occurs in the context of rigid domains. However, previous studies applying this methodology claim to produce independently validated results (Welford *et al.* 2018).

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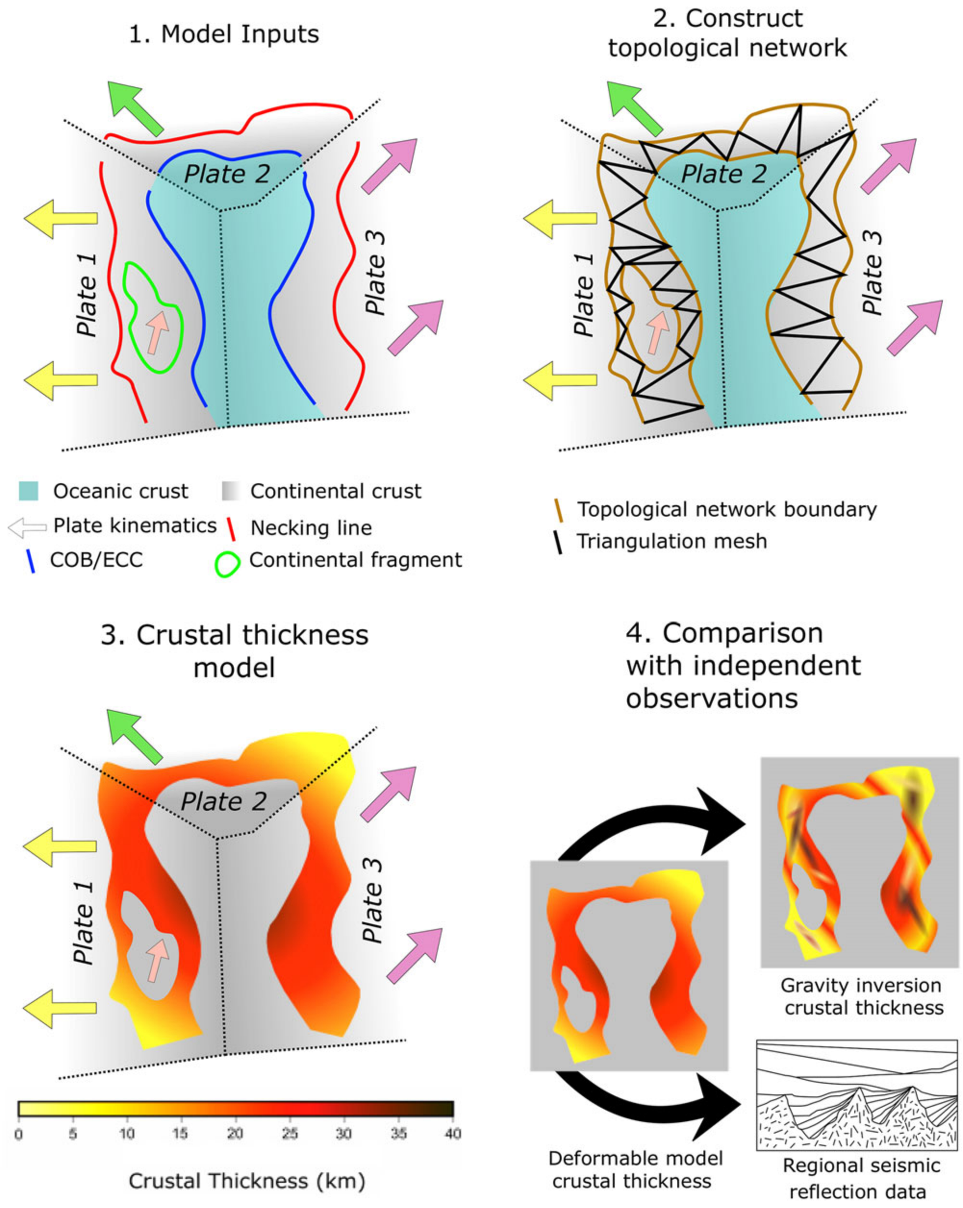

Fig. 2. (Colour online) Schematic depiction of the GPlates deformable plate tectonic modelling workflow followed by comparison with independent regional constraints modified after Peace *et al.* (2019) and King *et al.* (2020) based on methods described in Gurnis *et al.* (2018). Panel 1 shows the model inputs (deformable boundaries and optional interior features) required to construct a topological network. ECC = edge of continental crust, and COB = continent–ocean boundary. Panel 2 demonstrates the resultant triangulation mesh created after a topological network is constructed in GPlates. Panel 3 displays a crustal thickness model created using the deformable mesh constructed in panel 2. Panel 4 demonstrates the need to assess the validity of crustal thickness models created in GPlates against independent observations such as estimates from gravity inversion and observations from seismic data as in Welford *et al.* (2018).

Using the GPlates methodology, Müller *et al.* (2019) produced a global Mesozoic–Cenozoic deforming plate motion model that captures the progressive extension of all continental margins since the initiation of Pangaea's dispersal starting at ˜240 Ma. The Müller *et al.* (2019) model includes major failed continental rifts and compressional deformation. Müller *et al.* (2019) acknowledge that their global model will likely form the starting point for more regional models. The Müller *et al.* (2019) model includes deforming zones for an area of ˜8 % of the Earth's surface in which distributed deformation of the lithosphere occurs. However, Müller *et al.* (2019) note that this value is significantly smaller than other estimates (e.g. the Kreemer *et al.* (2014) 14 % estimate). Müller *et al.* (2019) state that the main reason for the discrepancy is that they solely focus on deformation of continental lithosphere, and therefore exclude large deforming regions in ocean basins. In addition, the model of Müller *et al.* (2019) also excludes deforming edges of overriding plates along subduction zones, which form another significant portion of the Kreemer *et al.* (2014) geodetic strain-rate model. The Müller *et al.* (2019) model was applied by Ebbing *et al.* (2021) to provide new insights into Gondwana's dispersal, demonstrating the applicability of such models.

At the regional scale, Peace *et al.* (2019) applied the GPlates deformable modelling workflow to the southern North Atlantic region by constructing a number of plate tectonic models and comparing the resultant crustal thicknesses with independently derived crustal thickness models from gravity inversion. This showed how resultant deformation from different plate models can be compared systematically. Similarly, Welford *et al.* (2018) applied the GPlates methodology to Baffin Bay showing that external model boundaries need to be a sufficient distance from the eventual location of break-up to prevent edge effects. King *et al.* (2020) studied the Galicia Bank on the Iberian margin and demonstrate that the GPlates methodology can be used to study structural inheritance. Gurnis *et al.* (2019) used the GPlates deformable plate modelling methodology to study the Puysegur Trench, New Zealand, and similarly Liu *et al.* (2021) used the GPlates deformable model workflow to study the subduction of the Pacific plate in East

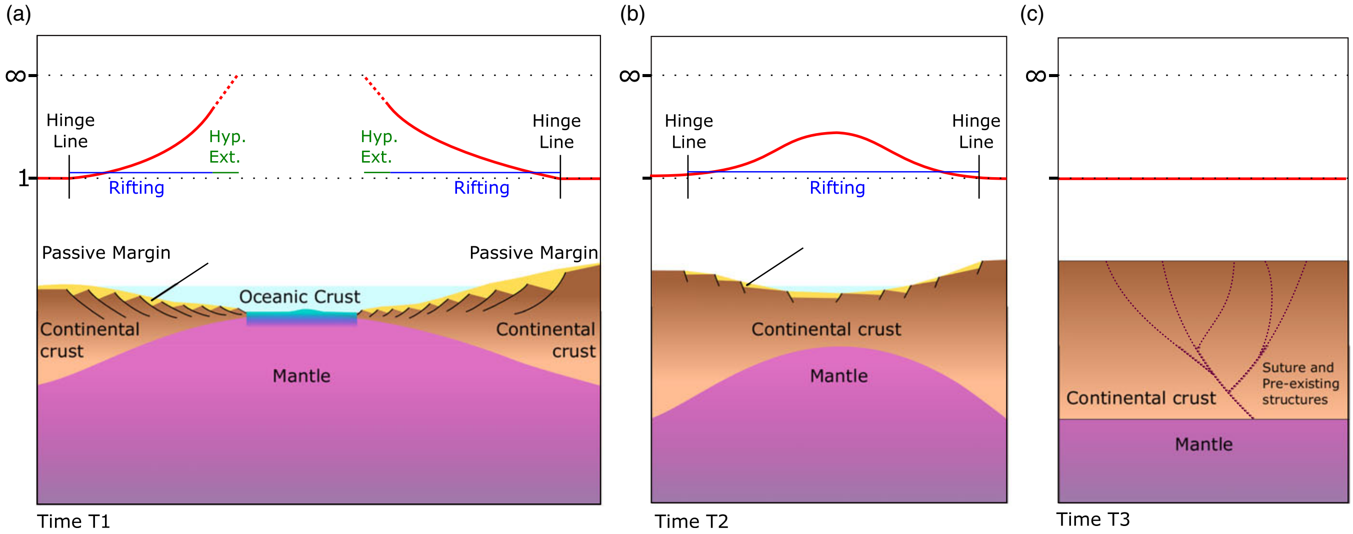

Fig. 3. (Colour online) Schematic demonstration of deformable restoration of a conjugate margin pair using an iterative palinspastic methodology as described in Ady & Whittaker (2019). T1–T3 refer to the time-steps in such an iterative methodology. (a) Present-day (0 Ma) cross-section through a post-break-up hyperextended conjugate margin pair showing total beta trending to ∞ due to hyperextension (Hyp. Ext.). (b) Active rifting stage showing the restored beta factor increasing towards the centre of the rift. (c) Restored cross-section to pre-rift configuration with inferred pre-existing structures and total beta equal to 1. The concepts in this figure are modified from Ady & Whittaker (2019) who show the Norwegian – East Greenland conjugate margin pair (e.g. Peron-Pinvidic *et al.*, 2012), including the Jan Mayen Microcontinent (e.g. Schiffer *et al.* 2019). The example shown here, however, does not contain a microcontinent and shows relatively symmetrical rifting.

Asia. Recently, Cao *et al.* (2020) applied this modelling workflow to the South China Block. The intraplate deformation in South China is closely related to the subduction of the Izanagi and Pacific plates. Thus, Cao *et al.* (2020) demonstrate the applicability at settings that include a compressional phase. Zhu *et al.* (2021) built a deformable plate model using GPlates of the Bohai Bay Basin in North China which is claimed to have implications for the entire East Asia region, demonstrating how insightful such reconstructions can be.

An alternative approach to deformable plate tectonic modelling has been developed and applied by Ady & Whittaker (2019) (Fig. 3). They produced a model for the entire North Atlantic region to study structural inheritance, and as an aid to exploration on the continental margins. Amongst other items, the inputs for the Ady & Whittaker (2019) model include a map of total beta (total beta = initial crustal thickness / final crustal thickness) in the model inputs. The map of total beta in the Ady & Whittaker (2019) workflow is calculated from crustal thickness obtained through gravity inversion and, where available, seismic data. A palinspastic deformation model guided by plate-derived Euler flowlines is then made in which deformation is iteratively restored. As with the GPlates models, the Ady & Whittaker (2019) models assume pure shear deformation and suggest that this is an adequate approximation at the scale of their study. Assumption of pure shear deformation in rift systems is not universally applicable, as many rifts have been shown not to obey symmetrical thinning (Becker *et al.* 2014; Peace *et al.* 2016).

Both the GPlates method (Gurnis *et al.* 2018) and the Ady & Whittaker (2019) method require that continent–ocean boundaries (COBs) are accurately defined both spatially and temporally. Peace *et al.* (2019) found that the timing and location of break-up plays a significant role in the resultant deformation. However, challenges in defining COBs and break-up ages have been noted (Eagles *et al.* 2015), presenting a problem for plate reconstructions. Ady & Whittaker (2019) suggest that most of the issues with COBs pointed out by Eagles *et al.* (2015) are unlikely to occur when COBs are picked consistently for the specific purpose of plate kinematic modelling. Nonetheless, it is clear this aspect of all plate models requires caution, particularly as the highly variable structure of passive margins is well documented (e.g. Biari *et al.* 2021).

Another major issue remains, in that plate movements for the Mesozoic are largely defined by reconstructions of the oceanic domain (Seton *et al.* 2012). As such, a common obstacle encountered during deformable plate tectonic modelling is availability of constraints. Deformation within continental domains often occurs during time periods when reliable plate kinematic constraints are scarce (King *et al.* 2020). The constraints on deformation in the continental domains are harder to obtain and less reliable compared to those from the oceanic domains such as datable (and globally correlatable) oceanic magnetic anomalies and fracture zones (Peace *et al.* 2019). Constraints on the deformation within continental domains can be derived from analysing rift styles, fault geometry, preserved continental fragments and the timing of deformation through stratigraphic evidence observed in seismic sections and well data (Peace *et al.* 2019). The limiting factor on deformable plate models is thus not the computational or methodological restrictions; rather, it is the need to obtain adequate constraints on timing and kinematics of deformation events. As the constraints on continental deformation are much poorer, modelling multiple scenarios is suggested (Peace & Welford, 2020).

3. Inclusion or omission of microcontinental fragments in plate models

It is well known that in rifts a number of different types of relatively undeformed regions of continental material may prevail despite surrounding deformation (Peron-Pinvidic & Manatschal, 2010; Foulger *et al.* 2020; Schiffer *et al.* 2019; Neuharth *et al.* 2021). The genetic origin of such entities may vary (Whittaker *et al.* 2016), as well as their size and degree of internal deformation, and they may be referred to as microplates, continental fragments, terranes, blocks, or by combinations of these or other terms

(Peron-Pinvidic & Manatschal, 2010). Here the term 'continental fragments' is used for consistency, but no preference over other comparable terms is implied. Previous work shows how the inclusion or omission of continental fragments in a model can profoundly influence plate models (Peace & Welford, 2020). As such, another theme in recent plate tectonic models is the defining of smaller regions that move independently. For example, in the Southern North Atlantic, Nirrengarten *et al.* (2018) defined a number of microcontinental fragments that, like the major plates, also have kinematics described by Euler poles. Likewise, Gion *et al.* (2017) reconstructed the Eurekan orogeny as a number of independent entities, each with its own Euler pole. These types of reconstructions address some of the same challenges that deformable models are attempting to solve. Moreover, models have been developed that include both independent smaller plates and deformable regions (Peace *et al.* 2019).

However, questions remain regarding how small it is possible to go when defining individual plates. For example, could it ever be feasible that individual fault blocks are defined in plate models with their own Euler pole? The reality is that everything in an actively deforming region can undergo variable degrees of deformation. Even the microcontinental fragments in models such as that of Nirrengarten *et al.* (2018) have likely undergone some amount of internal deformation (e.g. rift-related deformation on the Flemish Cap), and as such the unresolved question of where to draw the line between deforming and undeforming regions remains.

The necessity of including microcontinental fragments to produce a better fit has been questioned by Ady & Whittaker (2019) who argue that their quantitative restoration methodology provides an alternative to their inclusion. In the Ady & Whittaker (2019) model, only five independent plates for the entire North Atlantic region are defined, demonstrating that adequate deformable models can be produced without smaller plates. However, it has also been suggested that models that include both microcontinental fragments and a deformable modelling workflow are likely to give the most realistic reconstruction of deformation (Peace *et al.* 2019). It is thus clear that further investigation into the inclusion/omission of microcontinental fragments is necessary.

Another substantial and outstanding issue is how the constraints on the kinematics of continental fragments are derived. It has been suggested that through detailed mapping of structures in deformed regions the kinematics of continental fragments may be elucidated (King *et al.* 2020). However, even with the most detailed mapping, resolving deformation histories is problematic and many scenarios must be considered to give any level of validation to a model (Peace *et al.* 2019).

4. A classification system for deformable plate models: two fundamentally different types?

It is clear that not all deformable plate models are the same in terms of their capabilities, inputs and outputs. Ady & Whittaker (2019) propose a classification system with rigid, dynamic and deformable plate models, as well as subcategories. The Ady & Whittaker (2019) classification provides a good overview of the types of models. However, an alternative method of categorizing deformable models is through the required inputs, and specifically whether a model uses a beta/thinning factor as a model input or as a result. For example the Ady & Whittaker (2019) deformable model uses gravity inversion to derive crustal thickness which is then used to calculate beta factors. An iterative approach is then used to restore deformation. On the other hand, the GPlates methodology calculates a beta or stretching factor based on the relative movements of plates. Each of these approaches has different uses. The Ady & Whittaker (2019) method likely more accurately reproduces deformation, but as deformation is not purely driven by the plate motions this method cannot be used to compare different plate models as easily as the GPlates method. The GPlates method, on the other hand, can be used as a validation tool for rigid plate models, as the fact that deformation is only driven by rigid plates allows kinematic models to be evaluated. Specifically, comparison of the resultant crustal geometries produced through different models with independent estimates can be made (Welford *et al.* 2018). The question, however, remains of how best to validate the reconstructions depicted in deformable plate models.

5. Conclusions and future directions

Plate tectonic models have provided the backbone to which many other aspects of geoscience have been tied (Vérard, 2019), and deformable plate models represent a rapidly evolving area of this field (Ady & Whittaker, 2019). Plate models that account for deformation have undoubtably changed our approach to reconstructing and visualizing the past motions of the continents. However, important methodological variations exist. One of the most important variations is whether one of either beta factor, stretching factor or present-day crustal thickness is used as a model input, or whether deformation is solely driven by surrounding rigid regions. Related to this aspect, it is imperative to ensure that no circularity exists between model inputs and validation criteria. In addition, whether microcontinental fragments are included or omitted represents a substantial difference. Irrespective of model type, however, the primary limiting factor on deformable plate models is neither the computational nor methodological restrictions; rather, it is the need to obtain adequate constraints on timing and kinematics of deformation.

The majority of recently published deformable plate models have focused on extensional tectonic settings (e.g. King *et al.* 2020), likely due to the use of plate models as exploration tools on highly prospective continental margins, but also perhaps because the application of deformable model techniques to other settings (such as orogens) is harder. Future, work should focus on extending the deformable plate modelling concepts further into convergent plate tectonic reconstructions.

Future deformable plate models will likely seek to link deep-Earth processes with crustal deformation (Yoshida, 2010, 2013; Coltice *et al.* 2019), as well as include erosion and subsidence, and have a greater emphasis on application to non-extensional settings. In addition, despite substantial recent developments (Merdith *et al.* 2019, 2020), the issue of realistic and well-constrained plate reconstructions beyond the latest supercontinent cycle is outstanding. With deep-time reconstructions (i.e. beyond the latest supercontinental cycle) reliable constraints for deformable plate models are harder to obtain and should be the focus of future work. When reliable deformation constraints are unavailable, the approach of modelling multiple evolutionary scenarios is likely best. In addition, ongoing issues with the plate-mantle reference frame that underpins both rigid and deformable models are recognized (Müller *et al.* 2019). Finally, the application of deformable modelling approaches to palaeoclimatic and palaeoceanographic studies can clearly be extended. For example, more realistic deformation models could provide constraints on ocean gateway opening and connectivity between ocean basins and resultant climatic feedbacks.

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