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A plate tectonic scenario for the Iapetus and Rheic oceans

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ABSTRACT

The tectonics, dynamics, and biogeographic landscape of the early Paleozoic were dominated by the opening and expansion of one large ocean—the Rheic—and the diminution to terminal closure of another—Iapetus. An understanding of the evolution of these oceans is thus central to an understanding of the early Paleozoic, but their chronicle also presents a rich temporal profile of the Wilson cycle, illustrating continental-scale rifting, microcontinent formation, ocean basin development, arc accretion, and continent–continent collision. Nevertheless, contemporary paleogeographic models of the Iapetus and Rheic oceans remain mostly schematic or spatio-temporally disjointed, which limits their utility and hinders their testing. Moreover, many of the important kinematic and dynamic aspects of the evolution of these oceans are impossible to unambiguously resolve from a conceptual perspective and the existing models unsurprisingly present a host of contradictory scenarios. With the specific aim to resolve some of the uncertainties in the evolution of this early Paleozoic domain, and a broader aim to instigate the application of quantitative kinematic models to the early Paleozoic, I present a new *plate tectonic* model for the Iapetus and Rheic oceans. The model has realistic tectonic plates, which include oceanic lithosphere, that are defined by explicit and rigorously managed plate boundaries, the nature and kinematics of which are derived from geological evidence and plate tectonic principles. Accompanying the presentation and discussion of the plate model, an extensive review of the underlying geological and paleogeographic data is also presented.

1. Introduction

The opening of the Rheic Ocean (McKerrow and Ziegler, 1972) by the rifting of marginal terranes from northwest Gondwana, and the subsequent closure of the Iapetus Ocean (Harland and Gayer, 1972) by means of a three-way continental collision between Baltica, Avalonia, and Laurentia (Cocks and Fortey, 1982; Torsvik et al., 1996), arguably constitute the most dramatic, defining, and well-studied tectonic events of the early Paleozoic. An understanding of the evolution of these oceans is thus central to a broader understanding of the early Paleozoic. Moreover, as their history embodies a temporal cross-section through the transition of two major Wilson cycles, the chronicle of the Iapetus and Rheic oceans is also relevant to the study of global tectonics in general. However, notwithstanding a broad consensus on the first-order narrative (Torsvik and Trench, 1991), many aspects of this important tectonic saga remain unresolved. For example, among contemporary paleogeographic models that depict the opening of the Rheic, there are significant differences in the published number of independent terranes that rifted from northwest Gondwana, the manner in which they rifted, and in how and when those terranes arrived at the margins of Baltica and Laurentia (Cocks and Torsvik, 2002; Nance et al., 2010; van Staal and Hatcher, 2010; Pollock et al., 2011; Waldron et al., 2014). The differing terrane reconstructions in turn result in different ocean basin plans and provide contrasting examples of processes related to rifting, microcontinent formation, and ocean basin development.

Although additional data are (as always) desirable, many of the discrepancies among contemporary early Paleozoic paleogeographic models are driven not by a dearth of available data but by the limited adoption of the data available. In some models, this is partly due to the fact that the model was principally designed to fit the observations of a specific area (i.e. northern Appalachians, southern British Isles, etc.), and only later expanded to a larger region as a correlative exercise. However, a more significant shortcoming is that nearly all of the presently available models are schematic, or at least substantially spatio-temporally disjointed. That means that they are not bound to meet general conditions of tectonic feasibility or kinematic continuity, which greatly loosens a host of constraints that would otherwise be placed on them. Thus, there is a wealth of untapped ‘data’ in the form of practical tectonic considerations, which can greatly enhance our ability to critically evaluate existing models by further limiting the range of permissible tectonic scenarios.

It is extremely challenging to construct an early Paleozoic paleogeographic model on a rigorous plate tectonic framework because the entirety of the pre-Mesozoic oceanic lithosphere has been lost by subduction, save some minor relics preserved as ophiolites. Nevertheless, the kinematics of long-lost ocean basins can still be partly surmised through a careful analysis of the kinematics of the continents and

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terranes that formerly flanked them, together with the geological observations from their continental margins. By further uniting these inferred kinematics within a framework held to obey fundamental tectonic principles, a kinematic model that strictly conforms to both the observational data *and* basic plate tectonic rules can be built (Seton et al., 2012; Domeier and Torsvik, 2014). Such an approach can identify existing paleogeographic concepts that are inherently tectonically untenable, and those which work only in isolation.

Following this approach, this paper presents an early Paleozoic (500–420 Ma) plate tectonic model for the Iapetus and Rheic oceans that has been constructed to meet the available paleomagnetic, paleontological, and geological data, and which evolves in accordance with plate tectonic fundamentals. The result is a 'full-plate' model, wherein plate boundaries and oceanic lithosphere, in addition to the continents, are prescribed and advanced through the modeled interval. Such a full-plate model for the early Paleozoic is seen in the pioneering work of Stampfli and Borel (2002), but their model is based on a relative (Europe-fixed) kinematic network and its details are unfortunately industry confidential. In contrast, the model presented here is built from an absolute continental reconstruction (Torsvik et al., 2014), making it the first absolute, full-plate tectonic model for the early Paleozoic. Furthermore, the details of the presented model are freely distributed. The model should prove useful as a general paleogeographic reference and as an input for other modeling exercises, but should also serve as a shared research platform for the paleogeographic community. Ideally, the model can be tested against new observations and refined when necessary, so as to evolve in parallel with our collective understanding of early Paleozoic tectonics.

2. Methodology

The methodology in this study follows that in Domeier and Torsvik (2014), here reiterated succinctly. The plate tectonic model presented is built upon the continental reconstruction model of Torsvik et al. (2014), which itself is founded upon a global paleomagnetic dataset (Torsvik et al., 2012), a catalog of large igneous province (LIP) and kimberlite distributions (Torsvik et al., 2008, 2010) and a wealth of qualitative to semi-quantitative geological and paleontological data. These data, many of which are reviewed in the following sections and in Appendix A (available from journal website), provide the basis to reconstruct the continents through time. Notably, whereas paleolatitude can (ideally) be unequivocally determined from paleomagnetic data, paleolongitude is mostly ambiguous. Paleontological data can offer insights into the relative proximity of continents, and together with paleomagnetic data they may provide some constraints on relative longitude, but cannot determine absolute paleolongitude. Concerning absolute paleolongitude, Torsvik et al. (2008, 2010) showed that LIP and kimberlite occurrences of the last 320 Myr—when reconstructed to their original positions in a mantle reference frame—coincided with the margins of the large low shear velocity provinces (LLSVPs) in the lowermost mantle. Following the assumption that the LLSVPs have remained stable from the earliest Paleozoic, as they demonstrably have since the Mesozoic, it is possible to construct models with provisional absolute paleolongitude, when and where LIPs and kimberlites are found. This is a major assumption that requires further validation, but, significantly, the model presented herein demonstrates that it is at least *possible* to construct an early Paleozoic plate model under this paradigm.

With the time-dependent motions of the continents established, work proceeds with the reconstruction of ocean basin kinematics and the delineation of plate boundaries. The relative kinematics of the oceans can be inferred through careful integration and analysis of the geology from the margins of the continents, which can provide information about the relative motion (or lack thereof) of the oceanic lithosphere that once flanked them. For example, observations of arc magmatism, HP/UHP metamorphism, ophiolite obduction, etc. can reflect subduction, and thus convergence between a pair of plates, whereas rift-related sedimentation and volcanism, etc., may denote the onset of divergence. Similarly, structural relics can reveal the presence of a transcurrent boundary and determine the sense of motion that once occurred along it. By unifying the relative kinematics inferred from those geological records with the absolute kinematics of the continents, the absolute kinematics of the oceans can be constrained. The specification and temporal management of plate boundaries are likewise realized through the integration of the continental rotation model, continental geology, and basic plate tectonic principles. Plates are assumed to be rigid and their boundaries divisible into segments of divergent, transcurrent, and convergent motion. Along divergent boundaries, spreading is assumed to be symmetrical and orthogonal, and ridge segments themselves are assumed to follow the trace of a great circle passing through the Euler pole that defines the relative motion of the adjoining plates. No assumptions are made about the orientation of continental rifting that precedes seafloor spreading, and it can be highly oblique. Transform boundaries are assumed to follow the trace of a small circle about the Euler pole describing the relative motion of the adjoining plates. No comparably unique assumptions apply for estimating the orientation of subduction zones, but their locations can often be constrained through conservation (of surface area) considerations, and their polarity may be determinable from the geological record. Plate dynamic considerations are not inherent to construction of the model, but are occasionally invoked to discriminate competing scenarios that may be equally kinematically viable; these are discussed in Section 4.

Reconstruction of the ocean basins and the plate boundary network was conducted with the open-source software Gplates (Boyden et al., 2011) (www.gplates.org). The reconstruction of those elements was accomplished via an iterative process, since they are required not only to meet the constraints imposed by a given time but also to evolve in compliance with tectonic rules to fit the observations of other times. Additionally, solutions are often non-unique; in such cases, adoption of the simplest solution that satisfies the existing constraints has been sought. Equipped with the continental reconstruction model, inferred ocean basin kinematics, and the network of plate boundaries, the final plate model was built with continuously closing plate polygons, according to the method of Gurnis et al. (2012). Because the scope of the model is restricted to the domain of the Iapetus and Rheic oceans, it is encircled by an arbitrary perimeter used to close those plate polygons that moved partly beyond the frame of interest. It is important to note that this perimeter is geologically meaningless. Although the plate boundaries were implemented with an arbitrary time-stepping of 1 Myr, the temporal resolution of the plate model can be scaled according to the needs of the user.

3. Geological synopses

The following section presents interpretations of the early Paleozoic geology from the margins of the continents that flanked the Iapetus and Rheic oceans (Fig. 1), with a focus on the features that communicate information about plate interactions. The geological observations from which the interpretations have been drawn are summarized in Appendix A, together with overview maps and many additional references. The principal interpretations of this section are also presented in condensed form in Table 1. In this paper, geochronological units are referenced to the timescale of Walker et al. (2013) and the informal term 'early Cambrian' refers to epochs 1 (Terreneuvian) and 2 (unnamed), 'middle Cambrian' refers to epoch 3 (unnamed), and 'late Cambrian' refers to epoch 4 (Furongian). The informal term 'early Silurian' refers to the Llandovery, 'middle Silurian' refers to the Wenlock, and 'late Silurian' refers to the Ludlow and Pridoli. The term 'terrane' is used in an informal sense to refer to lithological units, presumed to be of the same affinity, that are demonstrated or inferred to cover fragments of continental basement. Some of these 'terranes' comprise yet smaller, possibly distinct units that could be classified as 'terranes' themselves.