Geoscience Frontiers 5 (2014) 303–350

Contents lists available at ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Focus paper

Plate tectonics in the late Paleozoic

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ARTICLE INFO

Article history:
Received 21 November 2013
Received in revised form
13 January 2014
Accepted 15 January 2014
Available online 28 January 2014

Keywords:
Late Paleozoic
Paleogeography
Plate tectonics
Plate kinematics
Paleomagnetism

ABSTRACT

As the chronicle of plate motions through time, paleogeography is fundamental to our understanding of plate tectonics and its role in shaping the geology of the present-day. To properly appreciate the history of tectonics—and its influence on the deep Earth and climate—it is imperative to seek an accurate and global model of paleogeography. However, owing to the incessant loss of oceanic lithosphere through subduction, the paleogeographic reconstruction of 'full-plates' (including oceanic lithosphere) becomes increasingly challenging with age. Prior to 150 Ma ~60% of the lithosphere is missing and reconstructions are developed without explicit regard for oceanic lithosphere or plate tectonic principles; in effect, reflecting the earlier mobilistic paradigm of continental drift. Although these 'continental' reconstructions have been immensely useful, the next-generation of mantle models requires global plate kinematic descriptions with full-plate reconstructions. Moreover, in disregarding (or only loosely applying) plate tectonic rules, continental reconstructions fail to take advantage of a wealth of additional information in the form of practical constraints. Following a series of new developments, both in geodynamic theory and analytical tools, it is now feasible to construct full-plate models that lend themselves to testing by the wider Earth-science community. Such a model is presented here for the late Paleozoic (410–250 Ma) together with a review of the underlying data. Although we expect this model to be particularly useful for numerical mantle modeling, we hope that it will also serve as a general framework for understanding late Paleozoic tectonics, one on which future improvements can be built and further tested.

1. Introduction

Since its origin in the nascent mobilistic concept of continental drift, as first put forth by Wegener (1912), paleogeography has come to be fundamental to our understanding and interpretation of geology and geophysics. But though Wegener had presented a late Paleozoic reconstruction (relative to Europe and Africa) a century ago, it wasn't until the plate tectonic revolution of the 1960s that the wider Earth-science community came to appreciate and adopt a mobilistic paradigm—and with it, the obvious significance of paleogeography. Ironically, since the development and acceptance of plate tectonics, work on pre-Cretaceous paleogeography has been almost exclusively conducted under the framework of the now-superseded theory of continental drift. Of course, paleogeographers have not rejected plate tectonics in favor of its archetype, but nonetheless, general considerations of plate boundaries and oceanic lithosphere are largely absent from pre-Cretaceous models. The reason for that is simple: due to the incessant destruction of oceanic lithosphere by subduction, information pertaining to the oceanic component of plates is progressively lost with time. Moving backward, at 150 Ma ~60% of the lithosphere is missing (Torsvik et al., 2010b), thus making a global 'full-plate' reconstruction exceedingly challenging prior to that time.

However, with the advent of powerful new geodynamic concepts (Torsvik et al., 2008b) and analytical tools (www.gplates.org), in addition to ever-growing libraries of paleogeographic data, it is now feasible to make significant progress on that front, which, in

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Peer-review under responsibility of China University of Geosciences (Beijing)

Production and hosting by Elsevier

1674-9871/$ – see front matter
http://dx.doi.org/10.1016/j.gsf.2014.01.002

effect, 'pushes' plate tectonics backward into early Mesozoic and Paleozoic time. The rationale for such effort is broad: not only will 'full-plate' reconstructions yield myriad testable scenarios, predictions, insights and novel questions, they are also necessary for the execution of next-generation numerical models (Bower et al., 2013; Bull et al., submitted for publication). Moreover, as it is certain that plate tectonics was operating in the early Mesozoic and Paleozoic, it is natural that we should strive to make models that conform to this framework.

Stampfli and Borel (2002) and Stampfli et al. (2013) first attempted to apply plate tectonic principles to the early Mesozoic and Paleozoic, producing a 'full-plate' (hereafter just 'plate') model with a careful accounting of plate kinematics and consideration of geodynamic forces. Unfortunately, the critical underpinning, industry-confidential details of their model are not accessible, and so it is impractical to test or improve. Seton et al. (2012) later paved the way with newly available and freely accessible tools, and released the details of a global plate model that extends back to the earliest Jurassic (200 Ma). Following their lead, we present here a global plate model that spans late Paleozoic time (410–250 Ma). Importantly, our model is constrained both by observational data and by plate tectonic principles, and includes explicitly prescribed plate boundaries and oceanic lithosphere that are rigorously managed throughout the modeled interval. Although we have endeavored to make this model conform to the existing observational record and thus expect that it will be useful as an input, reference and predictive tool, we also hope that it will prove suitably amenable to modification so as to act as an infrastructure for further improvements.

2. Methodology

2.1. Fundamental data and models

The foundation of our plate model is the continental reconstruction model of Torsvik et al. (submitted for publication), which itself is founded upon a global paleomagnetic dataset (Torsvik et al., 2012), a catalog of LIP and kimberlite distributions (Torsvik et al., 2008b, 2010a) and a wealth of qualitative to semi-quantitative geological and paleontological data. A further discussion of those data and their specific paleogeographic implications for our plate model follows in Section 4.

Paleomagnetism represents our single most valuable paleogeographical tool for times prior to the Cretaceous, but it can only be used to constrain latitude (longitude is indeterminate) and Paleozoic paleomagnetic records are only available from the continents. Furthermore, their quantity and quality are highly variable in both space and time, and thus are our constraints on paleolatitude. Unfortunately, some of the greatest deficiencies in the Phanerozoic dataset are found in our interval of interest. For example, only one paleomagnetic pole is available from Laurussia for 390–340 Ma, Siberia only has one reliable entry for the Devonian and Carboniferous and South China has no Carboniferous data. Where data are absent, interpolation is used to make a naïve estimate according to a smoothly varying spherical spline, but that approach is obviously limited—as always, more data are needed. Enticingly, a plate model loaded with other forms of data may be able to offer novel constraints on paleolatitude; we will revisit this idea in Section 5.2.

Concerning paleolongitude, Torsvik et al. (2008b, 2010a,b) 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 wave 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, we can construct models with provisional paleolongitude, when and where LIPs and kimberlites are found. However, reconstructions of this kind must be prepared in a mantle reference frame and therefore must first be corrected for true polar wander (TPW) (Torsvik et al., submitted for publication). In the late Paleozoic there were six known LIP eruptions and approximately 35 kimberlite emplacements, the latter mostly in Siberia and northern Laurussia.

Although paleontology only acts as a qualitative to semi-quantitative paleogeographical tool, it can prove invaluable in constraining paleolatitude or relative paleolongitude, particularly when other forms of data are ambiguous (i.e. indeterminate hemisphere or multiple LLSVP margins) or lacking. Such fossil data do not feature strongly in our following discussion, but they have played a prominent role in the continental reconstruction model which was our starting framework. Many specific reconstructions within this model are underpinned by observations of paleobiogeographical provinciality and/or temperature-sensitive biota, and much of that data has been reviewed in a series of papers by Cocks and Torsvik (2005, 2007, 2011, 2013) and Torsvik and Cocks (2004, 2009, 2011, 2013).

A variety of geological data were likewise used in the continental reconstruction model, some of which we review below. Our focus here is on those data which communicate information about plate interactions and dynamics, so readers looking, for example, for a treatment on the climate-sensitive facies data should refer to the papers cited above. Broadly, the compiled and presented geologic data include spatio-temporal details of regionally important episodes of magmatism, metamorphism and orogenesis, as well as key stratigraphic and structural relationships. They have been organized spatially, according to qualitatively defined margins, to facilitate the construction of simplified plate boundaries.

2.2. Construction of plate model

Using *GPlates* software (www.gplates.org), we have constructed a network of plate boundaries by drawing both from the relative motions described by the continental reconstruction model and from our interpretations of the compiled geological data (Section 3). From the geological data, observations of arc magmatism, HP/UHP metamorphism, ophiolite obduction, etc. can be used to infer the location, duration and polarity of a convergent margin, whereas rift-related sedimentation, volcanism, etc. may herald the development of a divergent one. Likewise, structural studies can communicate the style of a collisional event or the sense of motion along a transform boundary. By employing basic plate tectonic principles, the kinematic data extracted from the continental reconstruction model can be used to infer the character—and occasionally the location—of plate boundaries within the geographic domain of the continents. For example, in a purely divergent system, an Euler pole describing the relative motion between two continents would also describe the spreading between them. By assuming that the axis of the embryonic ridge approximates the trace of a great-circle passing through the Euler pole, and that spreading is symmetrical, the location and orientation of the plate margin can be tracked. It is similarly straightforward to predict the orientation of transform faults, since they follow the trace of a small circle about the Euler pole describing the relative motion of the bounding plates. In a global kinematic model, even geometrical considerations as simple as the conservation of area can provide great insight into the former positions and relationships of plate boundaries.

In practice, construction of the plate boundary network is an iterative process, as boundaries must not only meet the constraints imposed by a given time, but also evolve with kinematic continuity