Earth-Science Reviews 162 (2016) 293–337

Contents lists available at ScienceDirect

Earth-Science Reviews

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

Invited review

Tectonic evolution and deep mantle structure of the eastern Tethys since the latest Jurassic

Sabin Zahirovic [a,*], Kara J. Matthews [a,1], Nicolas Flament [a], R. Dietmar Müller [a], Kevin C. Hill [b], Maria Seton [a], Michael Gurnis [c]

[a] EarthByte Group, School of Geosciences, The University of Sydney, NSW 2006, Australia
[b] Oil Search Limited, Sydney, NSW 2000, Australia
[c] Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125, USA

ARTICLE INFO

Article history:
Received 30 September 2015
Received in revised form 1 September 2016
Accepted 5 September 2016
Available online 13 September 2016

Keywords:
Tethys
Pangea
Tectonics
Geodynamics
Sundaland
Southeast Asia

ABSTRACT

The breakup of Pangea in the Jurassic saw the opening of major ocean basins at the expense of older Tethyan and Pacific oceanic plates. Although the Tethyan seafloor spreading history has been lost to subduction, proxy indicators from multiple generations of Tethyan ribbon terranes, as well as the active margin geological histories of volcanism and ophiolite obduction events can be used to reconstruct these ancient oceanic plates. The plate reconstructions presented in this study reconcile observations from ocean basins and the onshore geological record to provide a regional synthesis, embedded in a global plate motion model, of the India-Eurasia convergence history, the accretionary growth of Southeast Asia and the Tethyan-Pacific tectonic link through the New Guinea margin.

The global plate motion model presented in this study captures the time-dependent evolution of plates and their tectonic boundaries since 160 Ma, which are assimilated as surface boundary conditions for numerical experiments of mantle convection. We evaluate subducted slab locations and geometries predicted by forward mantle flow models against P- and S-wave seismic tomography models. This approach harnesses modern plate reconstruction techniques, mantle convection models with imposed one-sided subduction, and constraints from the surface geology to address a number of unresolved Tethyan geodynamic controversies. Our synthesis reveals that north-dipping subduction beneath Eurasia in the latest Jurassic consumed the Meso-Tethys, and suggests that northward slab pull opened the younger Neo-Tethyan ocean basin from ~155 Ma. We model the rifting of 'Argoland', representing the East Java and West Sulawesi continental fragments, as a northward transfer of continental terranes in the latest Jurassic from the northwest Australian shelf – likely colliding first with parts of the Woyla intra-oceanic arc in the mid-Cretaceous, and accreting to the Borneo (Sundaland) core by ~80 Ma. The Neo-Tethyan ridge was likely consumed along an intra-oceanic subduction zone south of Eurasia from ~105 Ma, leading to a major change in the motion of the Indian Plate by ~100 Ma, as observed in the Wharton Basin fracture zone bends.

We investigate the geodynamic consequences of long-lived intra-oceanic subduction within the Neo-Tethys, requiring a two-stage India-Eurasia collision involving first contact between Greater India and the Kohistan-Ladakh Arc sometime between ~60 and 50 Ma, followed by continent-continent collision from ~47 Ma. Our models suggest that the Sunda slab kink beneath northwest Sumatra in the mantle transition zone results from the rotation and extrusion of Indochina from ~30 Ma. Our results are also the first to reproduce the enigmatic Proto South China Sea slab beneath northern Borneo, as well as the Tethyan/Woyla slab that is predicted at mid-mantle depths south of Sumatra. Further east, our revised reconstructions of the New Guinea margin, notably the evolution of the Sepik composite terrane and the Maramuni subduction zone, produce a better match with seismic tomography than previous reconstructions, and account for a slab at ~30°S beneath Lake Eyre that has been overridden by the northward advancing Australian continent. Our plate reconstructions provide a framework to study changing patterns of oceanic circulation, long-term sea level driven by changes in ocean basin volume, as well as major biogeographic dispersal pathways that have resulted from Gondwana fragmentation and accretion of Tethyan terranes to south- and southeast-Eurasia.

* Corresponding author.
E-mail address: sabin.zahirovic@sydney.edu.au (S. Zahirovic).
[1] Present address: Department of Earth Sciences, University of Oxford, South Parks Road, Oxford OX1 3AN, UK.

http://dx.doi.org/10.1016/j.earscirev.2016.09.005
0012-8252/

Contents

1. Introduction . . . 294
   1.1. Plate tectonic models of the eastern Tethys . . . 297
   1.2. Seismic tomography constraints . . . 299
   1.3. Numerical modelling of Tethyan geodynamics . . . 300
      1.3.1. Numerical models of India-Eurasia convergence . . . 301
      1.3.2. Numerical modelling of Southeast Asia and New Guinea geodynamics . . . 303
2. Methods . . . 303
   2.1. Plate tectonic reconstructions . . . 303
   2.2. Insights from seismic tomography . . . 305
   2.3. Coupled plate reconstructions and mantle convection numerical models . . . 307
3. Regional tectonic evolution . . . 309
   3.1. Late Jurassic plate boundary configuration and rifting mechanism along northern Gondwana . . . 309
   3.2. Active margin evolution in the Lhasa segment . . . 312
   3.3. Convergence along the West Burma and Sumatra margin segment . . . 314
      3.3.1. Development of the Woyla intra-oceanic arc . . . 315
      3.3.2. Subduction of the Woyla back-arc basin . . . 317
   3.4. Accretionary history of the Java and Borneo margin segment . . . 319
      3.4.1. Subduction and accretion history of southern Sundaland . . . 320
      3.4.2. Northern Sundaland collisions . . . 322
      3.4.3. Sundaland oroclinal bending . . . 322
   3.5. New Guinea and the Philippines . . . 322
      3.5.1. Origin and evolution of the Philippine Archipelago . . . 322
      3.5.2. Nature of the New Guinea margin since the Late Jurassic . . . 324
4. Insights from age-coded slabs in seismic tomography . . . 326
5. Numerical modelling results . . . 328
   5.1. Large-scale post-Jurassic mantle evolution of the Tethyan tectonic domain . . . 328
   5.2. Regional interpretations of mantle evolution . . . 328
      5.2.1. India-Eurasia convergence . . . 328
      5.2.2. Woyla and Sumatra active margin evolution . . . 330
      5.2.3. Java and Borneo subduction history . . . 330
      5.2.4. New Guinea margin evolution . . . 330
6. Discussion . . . 331
   6.1. Intra-oceanic subduction in the Meso- and Neo-Tethys . . . 331
   6.2. Southeast Asia and New Guinea . . . 331
   6.3. Relevance to global plate reconstructions and geodynamics . . . 332
7. Conclusions . . . 332
Acknowledgements . . . 332
References . . . 333

1. Introduction

Southern Eurasia, Southeast Asia and New Guinea represent a unique example of long-term tectonic convergence between multiple tectonic domains that has resulted in a complex assemblage of continental fragments, intra-oceanic arcs, ophiolite belts and marginal basins (Figs. 1 and 2). The Southeast Asian continental promontory, known as Sundaland, has grown through successive accretionary episodes resulting from the breakup of Pangea (Acharyya, 1998; Audley-Charles, 1988; Metcalfe, 1994), and subsequent northward transfer of Gondwana-derived continental ribbon terranes and microcontinents on the Tethyan oceanic "conveyors" towards Eurasia. Importantly, the region records a complex interaction between the Tethyan and (proto-) Pacific tectonic domains, which has opened and consumed successive oceanic basins and gateways (Metcalfe, 1999), and has had major consequences for biogeographic dispersal pathways such as the origin of the Wallace Line (Burrett et al., 1991; de Bruyn et al., 2014; Lohman et al., 2011; Monod and Prendini, 2015; Rolland et al., 2015), oceanic circulation (Gaina and Müller, 2007; Gourlan et al., 2008; Heine et al., 2004), global climate and sea level (Herold et al., 2014; Huber and Goldner, 2012; Lee et al., 2013; R.J. Morley, 2012; Müller et al., 2008; Scotese et al., 1999; Spasojevic and Gurnis, 2012; van der Meer et al., 2014; Wang, 2004; Xu et al., 2012), and the development of economic resources (Goldfarb et al., 2014; Zaw et al., 2014).

Plate tectonic reconstructions play a pivotal role in unravelling the complexity of this region and provide a platform to address long-standing geological questions in a geodynamic context. We apply a modern approach of modelling entire plates, their evolving plate boundaries and the terranes they carry. This study aims to synthesise previously published onshore and offshore geological constraints, as well as incorporate decades of developments in plate tectonic reconstructions, into a modern plate motion model to document the post-Pangea geodynamic evolution of southern Eurasia, Southeast Asia and New Guinea since the Late Jurassic in a regional and global context. Despite significant technological and methodological advancements in plate reconstruction approaches, very few reconstructions of the eastern Tethys exist in an open-access digital form that can be tested and expanded by the scientific community.

As part of this work, we release detailed plate reconstructions for the eastern Tethys (from the India-Eurasia collision zone eastward to Papua New Guinea, Figs. 1–3) that are embedded in a self-consistent global plate motion model, as a collection of digital geometry files and rotation parameters compatible with the open-source and cross-platform plate reconstruction tool, GPlates (www.gplates.org). We provide a brief background to previous regional tectonic reconstructions in Section 1.1, as well as tomographic and numerical modelling approaches in Sections 1.2–1.3 that have been used to gain insight into the tectonic and geodynamic processes controlling the regional evolution. In Sections 2 to 4, we outline our approach of building modern plate reconstructions for the three key regions that comprise the eastern Tethys, including i) the India-Eurasia convergence zone, ii) Southeast Asia, and iii) the New Guinea margin, and compare our approach and findings with previous work. In Section 5, we show how modern plate