Gondwana Research 28 (2015) 612–624

Contents lists available at ScienceDirect

Gondwana Research

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

The tectonic stress field evolution of India since the Oligocene

R.D. Müller [a,*], V. Yatheesh [b], M. Shuhail [b]

[a] *EarthByte Group, School of Geosciences, University of Sydney, NSW 2006, Australia*
[b] *CSIR — National Institute of Oceanography, Dona Paula, Goa 403 004, India*

ARTICLE INFO

Article history:
Received 15 August 2013
Received in revised form 12 May 2014
Accepted 21 May 2014
Available online 17 June 2014

Handling Editor: A.R.A. Aitken

Keywords:
Palaeo-stress
Indo-Australian Plate
Tectonic reactivation
Intraplate stress
Wharton Basin
Neotectonics

ABSTRACT

A multitude of observations suggest neotectonic deformation in and around India, but its causes and history are unknown. We use a 2 dimensional finite element model with heterogeneous elastic strengths in continental regions to model the regional stress field orientation and relative magnitudes since the Oligocene. The large-scale geological structure of India is embedded in our model by using published outlines of cratons, fold belts and basins, associated with estimates of their relative strengths, enabling the modelling of stress field deflections along interfaces between relatively strong and weak tectonic elements through time. At 33 Ma a roughly NNW–SSE oriented band of relatively high maximum horizontal compressive stress (S_{Hmax}) straddled India's west coast, while India's east coast and the adjacent Wharton Basin were characterized by relatively low intraplate stresses. Between 20 Ma and the present growing collisional boundary forces combined with maturing mid-ocean ridge flanks result in the establishment of an arcuate belt with anomalously high intraplate stress that stretches from India to the Wharton Basin, intersecting the continental shelf roughly orthogonally and crossing the 85° East and Ninetyeast ridges. This results in a compressive tectonic regime favouring folding and inversion north-east of the Godavari Graben on India's east coast, as observed in seismic reflection data, whereas no tectonic reactivation is observed on the continental margin further north, closer to the Mahanadi Graben, or further south. Our stress models account for these differences via spatial variations in modelled horizontal stress magnitudes and intersection angles between margin-paralleling pre-existing basement structures and the evolving Neogene stress field. The models further account for fracture zone strike-slip reactivation offshore Sumatra and lithospheric folding along India's west and southeast coast and can be used to estimate the onset of these deformation episodes to at least the Oligocene and Miocene, respectively.

1. Introduction

Diffuse plate boundary deformation in the equatorial Indian Ocean is well understood in the context of the fragmentation of the Indo-Australian Plate following India–Eurasia collision. The progressive collision between India and Eurasia since the Oligocene has produced the largest intra-oceanic fold and thrust belt on Earth (Royer and Gordon, 1997). Its effects on the progressive deformation of the Central Indian Basin (Krishna et al., 2009; Bull et al., 2010), the breakup of the Indo-Australian Plate into the Indian, Capricorn and Australian plates (Gordon et al., 1998; DeMets et al., 2005), the first-order plate-wide stress field (Cloetingh and Wortel, 1986; Coblentz et al., 1998) as well as the detailed Australian stress field evolution (Dyksterhuis and Müller, 2008; Müller et al., 2012) have been studied. Published seismic profiles document folding on the eastern Indian continental shelf west of the northern segment of the 85° East Ridge (Bastia et al., 2010; Radhakrishna et al., 2012), an observation not accounted for by current tectonic models. A variety of observations related to the evolution of intraplate deformation can be analysed in the context of current and past intraplate stresses. The present-day stress field of the central Indian Ocean has been studied extensively, revealing regional patterns of extension in the west versus compression in the east of the central Indian Basin, and illuminating the role of the Chagos–Laccadive and Ninetyeast ridges in controlling the style of deformation (Delescluse and Chamot-Rooke, 2007; Sager et al., 2013). There are sophisticated published models for understanding global plate driving forces and lithospheric stresses, focussing on either the effect of mantle forces (Steinberger et al., 2001), or both mantle forces, large-scale lithospheric structure and topography (Lithgow-Bertelloni and Guynn, 2004; Ghosh and Holt, 2012; Ghosh et al., 2013). However, these models are all confined to the present-day and have never been applied to the geological past. The reason for this is that various key model inputs and observations are not easy to quantify for the geological past. There is no global palaeo-stress map for any time in the past. By the same token, we don't know palaeotopography very well, a case in point being the Tibetan Plateau, where there are widely diverging interpretations of the evolution of Tibetan Plateau elevation, even at relatively recent times. In a recent review, Molnar et al. (2010) noted that the Tibetan Plateau elevation history cannot be quantified, but it seems likely that

---

[*] Corresponding author. Tel.: +61 2 9036 6533; fax: +61 2 9351 2442.
E-mail address: dietmar.muller@sydney.edu.au (R.D. Müller).

http://dx.doi.org/10.1016/j.gr.2014.05.008
1342-937X/

by 30 Ma a huge area north of Asia's pre-collisional southern margin extended from 20–25°N to nearly 40°N with a mean elevation perhaps as high as 1000 m. In the same year Song et al. (2010) estimated Tibetan Plateau elevation to have been at least 3000 m since even earlier times, i.e. the Eocene. These large uncertainties make it difficult to use palaeoelevation estimates in palaeo-stress models. In addition sparse geological and geophysical observations need to be used to ground-truth palaeo-stress models, such as folding and faulting visible in seismic reflection lines across sedimentary basins and margins (Gombos et al., 1995; Bastia and Radhakrishna, 2012), rock microstructures from outcrops (Letouzey, 1986; Sippel et al., 2010) and fracture systems in chalk (Duperret et al., 2012). The sparsity of these data, which are additionally not compiled in any database (unlike present-day stress data) implies that the generation and testing of sophisticated lithospheric stress models for the geological past are challenging, as some key boundary conditions like topography and mantle structure are not well known, nor are there rich and spatially dense data available for model validation. For the Indian subcontinent and the surrounding ocean crust a diverse range of observations have been used to constrain the nature and timing of tectonic reactivation, ranging from mapping and modelling of folding and faulting of ocean crust in the central Indian Basin (Royer and Gordon, 1997; Krishna et al., 2009), the mapping of river palaeo-channels (Subrahmanya, 1996), using geologic, geomorphic, and tide-gauge data to detect lithospheric buckling (Bendick and Bilham, 1999), measuring fault activity and slip rates (McCalpin and Thakkar, 2003; Banerjee et al., 2008; Clark and Bilham, 2008) and analysing Quaternary intraplate seismicity (Bilham et al., 2003) (Table 1). However, to date there are no published models of the intraplate stress evolution of the Indian subcontinent, nor for any other continent, with the exception of Australia (Müller et al., 2012). Modelling of the Australian palaeo-stress field (Müller et al., 2012) has shown that if the horizontal continental stress field is strongly dominated by compressional edge forces, i.e. collisions and mid-ocean ridge forces, the first-order features of the stress field are well captured without including mantle forces or topography. A major problem with including mantle forces in palaeo-stress models is our lack of knowledge of asthenospheric viscosity and its spatial and time-dependent variation, which is the main parameter governing how well mantle convection is coupled to a given plate or continent. This uncertainty is expressed in the great controversy over the influence of mantle convection and plume driving forces on the time-varying speed of the Indian Plate since the Late Cretaceous (Kumar et al., 2007; Cande and Stegman, 2011; van Hinsbergen et al., 2011), versus the effect of climate change (Iaffaldano et al., 2011) or changes in subduction geometry (Müller, 2007).

Despite the great uncertainties in palaeo-stress field modelling, the sparsity of data and the simplicity of current modelling approaches, our motivation for exploring relatively simple palaeo-stress models for India is the substantial interest in understanding the evolution of continental stress fields, for instance to unravel the formation and reactivation of structural hydrocarbon traps on the continental shelf (Gombos et al., 1995; Bastia and Radhakrishna, 2012) and for understanding the tectonic history of mobile belts and adjacent regions and their links with deep Earth resources.

Here we focus on modelling the evolution of India's palaeo-stress field. We combine observations related to different time scales, using the world stress map database (years to thousands of years) as well as structural reactivation and sediment folding visible in seismic reflection data (millions of years). Our study is focused on modelling the palaeo-continental stress field, as opposed to building a detailed model for the present-day field. Our oceanic model lithosphere has a relatively simple structure, unlike the detailed models by Delescluse and Chamot-Rooke (2007) and Sager et al. (2013), which take into account the effect of aseismic ridges, seamount chains and other structural discontinuities on instantaneous deformation of the ocean crust. Our relatively simple models are not designed to compete with these more sophisticated plate deformation models for the present day. Instead our models are deliberately simplified in oceanic realms to allow us to restore now subducted ocean crust, whose detailed local structure is not known, and to primarily focus on modelling the past continental stress field. For palaeo-stress field models the data available for model testing or validation are tiny in quantity and very different in character compared with the wealth and diversity of data constraining the present-day stress field (Heidbach et al., 2007). Tectonic reactivation through geological time is mainly reflected in faulting and folding preserved in basin and margin sediments, imaged by seismic reflection profiles. The model presented in this paper, designed to understand the palaeo-stress field evolution of India, is the first of its kind; in addition to providing a first-order basis for understanding the nature and driving forces of structural reactivation in India and along its margins, it also provides an intriguing hint that the evolution of plate-driving forces and far-field stresses since the Miocene may allow us to better understand the concentration of intraplate stress south of Sumatra.

2. Model setup

We construct the first palaeo-stress model for India by applying a well-established palaeo-stress modelling methodology (Dyksterhuis et al., 2005a,b; Dyksterhuis and Müller, 2008) to model its lithospheric stress field and the surrounding oceanic crust for three time slices, the Late Oligocene (33 Ma), the early Miocene (20 Ma) and the present. These times were chosen because they represent tectonic events seen in India–Eurasia convergent rate graphs (Zahirovic et al., 2012). Palaeo-stress modelling of the Australian continent has shown that both present and past stress fields can be well approximated by plate boundary stresses alone when the stress field is dominated by collisional forces, largely balanced by mid-ocean ridge forces (Müller et al., 2012). In these static palaeo-stress models one side of the perimeter of a given plate needs to be kept fixed, and in our case we use the Tibetan Plateau. This means that instead of depending on the need to know the combination of forces actually acting on that side of the plate, including its topography, all other boundary forces acting on the plate are balanced by an equivalent force along the side that is being held fixed. The applied forces are optimised to best match present-day stress

Table 1
Chronology of Neogene tectonic events on and around the Indian subcontinent. [1] Royer and Gordon (1997); [2] Krishna et al. (2009); [3] Bilham et al. (2003); [4] Subrahmanya (1996); [5] Banerjee et al. (2008); [6] Clark and Bilham (2008); [7] McCalpin and Thakkar (2003); and [8] Bendick and Bilham (1999).

Tectonic event	Timing	Evidence	Reference
Intraplate deformation in Central Indian Basin	Mid-Miocene	Large-scale folding & faulting	[1], [2]
Quaternary seismicity	Quaternary	Large magnitude earthquakes (e.g. Bhuj, Latur, Koyna)	[3]
Uplift of southern Indian peninsula	Quaternary	Migration of palaeo-channels, seaward shift of bathymetry contours	[4]
Rise of Shillong Plateau	Miocene	Acceleration of fault slip rates along the Shillong Plateau	[5], [6]
Tectonic uplift in Kachchh	Early Quaternary	Activities along E–W trending Katrol Hill Fault	[7]
Tectonic uplift in Kachchh	Late Pleistocene	Activities of transverse strike-slip faults	[7]
Lithospheric buckling along southwest coast of India (200 km wavelength)	Quaternary	Geologic, geomorphic, and tide-gauge data	[8]