Marine and Petroleum Geology 59 (2015) 406–428

Contents lists available at ScienceDirect

Marine and Petroleum Geology

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

Research paper

Repeat ridge jumps and microcontinent separation: insights from NE Arabian Sea

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ARTICLE INFO

Article history:
Received 14 November 2013
Received in revised form
31 May 2014
Accepted 26 August 2014
Available online 18 September 2014

Keywords:
Ridge jump
Seychelles–India separation
Laxmi ridge
Gravity modelling
Volcano-stratigraphy

ABSTRACT

Microcontinents separate due to ridge jumps associate either asymmetric sea floor spreading or plume–ridge interactions. India separated from Seychelles at ~64 Ma by asymmetric sea floor spreading initially when the spreading centre in the Mascarene Basin jumped towards the Indian sub-continent between magnetic chrons C29 and C28. The subsequent tectonics is difficult to comprehend since Laxmi Ridge-another microcontinent-formed during the later phase. Most of the studies considered the Laxmi Ridge as a sliver. Others considered it to be oceanic crust. High resolution, deep (~25 km) seismic data reveals that (*i*) the ridge possesses > 15 km deep sea-ward dipping reflector (SDR) packages; (*ii*) normal faulted rift valleys devoid of syn-rift sedimentary packages; and (*iii*) axial magma chambers 5–7 km beneath the ridge top. Additionally, from 2D forward gravity models we deduce that the ridge most possibly comprises of high density (oceanic) crust. We conclude the Laxmi Ridge to be indeed composed of oceanic crust and a fossil spreading centre. We thus identified the ridge jumps and their relation to the Seychelles microcontinent separation.

Previous numerical models suggest that the time required for a ridge jump is controlled by magmatic heating, spreading rate at the ridge, and plate ages. For repeated ridge jumps, the additional factor is the dynamic relation between the plume and lithosphere in terms of melt transfer and heating. We find that the medium spreading rates and high magmatic heating due to the Réunion plume and young plates favoured rapid and repeated ridge jumps towards the plume.

1. Introduction

Microcontinents or continental slivers (Müller et al., 2001; Péron-Pinvidic and Manatschal, 2010) develop commonly during continental breakup as either emergent e.g. Seychelles- or Jan Mayen Microcontinent (see Rey et al., 2003; Scott et al., 2005; Péron-Pinvidic et al., 2010) or buried e.g. Elan Bank (see Borissova et al., 2003) masses of continental crust ‘floating’ on oceanic lithosphere. The Seychelles is one of the best examples of a microcontinent since it has Precambrian granitic outcrops and is surrounded by oceanic crust (Schlüter, 2006; Hammond et al., 2013). Their genesis is attributed to two processes: *(i)* plume-assisted ridge propagations/jumps (Mittelstaedt et al., 2008, 2011); and *(ii)* spreading asymmetries at mid-oceanic ridges and resulting ridge reorganizations (Goff and Cochran, 1996). The Seychelles microcontinent separated from India at ~64–62 Ma (Collier et al., 2008) with prolific volcanism affecting India and Seychelles during Late Cretaceous to Early Paleocene (Chenet et al., 2007; references therein; Owen-Smith et al., 2013), popularly known as Deccan Traps for the onland volcanics (Mahoney, 1988) (Fig. 1). The track of the Réunion plume, related to the Seychelles-India separation, is demarcated by the Chagos-Maldive-Laccadive Ridge up to the Central Indian Ridge (CIR, Fig. 1; Duncan, 1990; Biswas, 2014). The Chagos-Maldive-Laccadive Ridge crossed the CIR to form the Saya de Malha bank (Fig. 1)- a sea mound with unconfirmed crustal nature (Eagles and Wibisono, 2013). The Chagos-Maldive-Laccadive Ridge might have continental fragments broken off during India-Madagascar separation (Nair et al., 2013; Torsvik et al., 2013). The NW-SE segment of the CIR is known as Carlsberg Ridge (Fig. 1). Thus, a combination of the rifting and volcanism formed one of the largest and most elegant magma-rich rifted passive margins. Magma-rich/magmatic/volcanic passive margins (Levell et al., 2010; Manatschal and Karner, 2012), as

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http://dx.doi.org/10.1016/j.marpetgeo.2014.08.019

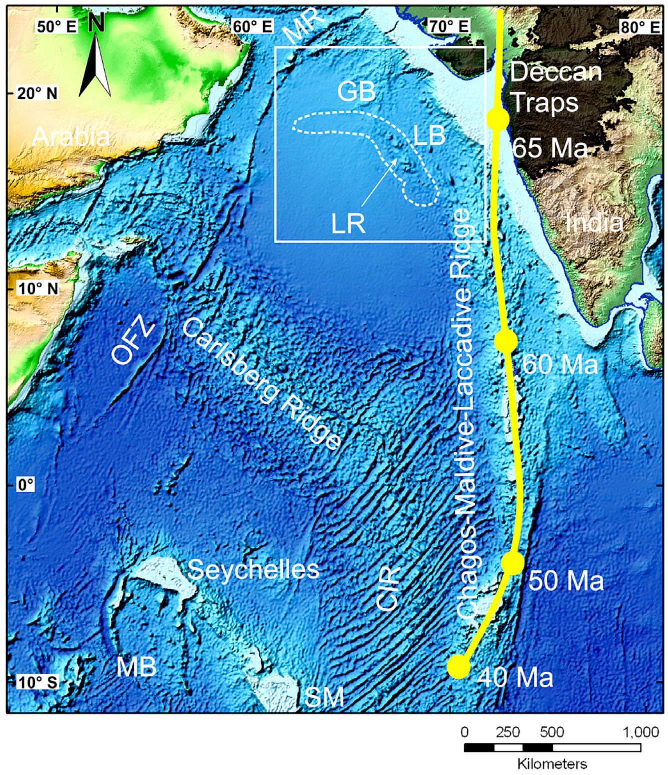

Figure 1. Map of the study area, within white rectangle. Adjoining areas with hill shaded bathymetry and topography. Areal extent of the Deccan Traps is shown in dark grey in the N part of the W continental margin of India. White dotted line: extent of the Laxmi Ridge. MR = Murray Ridge, LR = Laxmi Ridge, LB = Laxmi Basin, GB = Gop Basin, OFZ = Owen Fracture Zone, SM = Saya de Malha bank; MB = Mascarene Basin, CIR = Central Indian Ridge. Thick solid line: track of the Réunion hotspot (from Duncan, 1990). Bathymetry data: from Sandwell and Smith (2009); topography data: from Becker et al. (2009). This topography and bathymetry data, in a similar colour scheme, is used by other authors (e.g. Eagles and Wibisono, 2013) and thus this map may seem identical to those. Modified from fig. 1 of Misra et al. (2014).

opposed to magma-poor/amagmatic/non-volcanic margins (Manatschal, 2004; Whitmarsh and Manatschal, 2012), are characterised by relatively high volume of syn-rift volcanics and are associated commonly with mantle plumes (Menzies et al., 2002; Franke, 2013; Misra and Mukherjee, in preparation). Plumes are relevant in "active" rifting at magma-rich margins (Courtillot et al., 1999; Müller et al., 2001). India-Seychelles rifted from Madagascar by spreading the sea floor asymmetrically in the Mascarene Basin till chron C27 (Bernard and Munschy, 2000; Müller et al., 2001). This led a ridge jump towards the Réunion hotspot (Dyment, 1998). The magnetic anomalies indicate the ridge jump at chron C28 (63.4 Ma) (Collier et al., 2008). See figure 16.5 of Arora et al. (2003) for magnetization distribution map of Indian continent and surrounding region. Mahadevan (1994) reviewed gravity magnetic and seismic findings of our present study area. Rifting between Seychelles and India generated an "enigmatic" feature: the Laxmi Ridge (Todal and Edholm, 1998) (Fig. 2). This ~100 km wide and complex ridge is ~ E–W elevated basement at N from 63 to 66° longitude and ~ NW-SE at S from 19 to 14° N latitude (review: Prodehl and Mooney, 2012; also see Valdiya, 2010). Figure 2 shows the possible extent of the Laxmi Ridge mapped from free air gravity anomaly data, as in previous studies. The petroleum producing giant "Bombay High" ('BH' in Fig. 2) and other fields are located E to the study area (see Biswas, 2012). The Laxmi Ridge is a gravity low skirted by gravity highs. A sharp change in gravity of ~ 60 mGals defines the boundary.

The plume-ridge interaction and ridge jumps within chron C28–C26 has neither been studied well (e.g. Minshull et al., 2008) nor is straightforward. This is because previous workers considered the Laxmi Ridge to be a continental sliver (Naini and Talwani, 1982; Bhattacharya et al., 1994; Talwani and Reif, 1998; Todal and Edholm, 1998; Krishna et al., 2006; Collier et al., 2008) based on gravity inversion modelling, shallow seismic data, and seismic refraction lines and points.

This study, entirely in the submarine realm of the Indian plate (Fig. 1), re-examines the Laxmi Ridge with vintage single channel seismic lines (from Lamont-Doherty through GeoMapApp; http://www.geomapapp.org) and high resolution reflection seismic lines of long (18 s) record length (from ion-GX Technology), seismic refraction points data (from Naini and Talwani, 1982), reinterpretation of the gravity- (Sandwell and Smith, 2009) and magnetic anomaly data (Maus et al., 2007) constrained with the reflection seismic data, seismic volcanostratigraphy and well data to unravel its crustal structure. We interpret seismic facies on the seismic sections to understand the geology of the region and corroborate with the geophysical constraints (gravity, compressional wave velocity and magnetic). Did plume-assisted ridge jumps separate the Seychelles microcontinent? Or, did severing happen by asymmetric spreading in the NE Arabian Sea, after the ridge jump from the Mascarene Basin? We infer the crustal nature of the Laxmi Ridge from seismic and gravity data and interpret the magnetic data to study the chronology of the ridge jumps related to the Seychelles microcontinent separation. Understanding tectonics of the study area is important in hydrocarbon exploration (e.g. Biswas, 1989; Vaidyanadhan and Ramakrishnan, 2008).

2. Regional context

2.1. Tectonic elements

The important aseismic ridges in the Arabian Sea are the Laxmi-, Comorin-, Chagos-Maldive-Laccadive ridges. The Carlsberg- and the Central Indian Ridges are active spreading centres; the Owen Fracture Zone is a > 3000 km long ~ NNE trending fracture zone separating the Indian- and Arabian plates (Fig. 1; Kearey et al., 2009). The Owen Fracture Zone continues NE as the Murray Ridge. The Murray Ridge is considered as a Mesozoic oceanic block deformed under transpression by the sinistral Owen Fracture Zone during Early Paleocene and by transtension during Oligo-Miocene (Corfield et al., 2010). The Laxmi Ridge, an important tectonic element, is located W to the western continental sheared margin of India. Sheared or oblique continental passive margins, as opposed to orthogonal ones, are those where the net extension is not perpendicular to the margin (e.g. Green, 2011; Baudot et al., 2013). Evidences of shearing in the margin have been reported from onland and offshore studies around Mumbai (shelf) region (Ghosh and Zutshi, 1989; Misra et al., 2014). S to the present study area, the Konkan-Kerala margin formed by oblique rifting of Madagascar from India (Subrahmanyam and Chand, 2006; Reeves, 2013, 2014). The Laxmi Ridge (Fig. 2) divides the northern Arabian Sea into Western-and Eastern Basins (Naini and Talwani, 1982; reviews by Bastia and Radhakrishna, 2011). The Western Basin starts from the S/SW edge of the ridge and continues up to the present day Carlsberg Ridge (Krishna et al., 2006). The Laxmi Basin (LB in Fig. 1) represents the region between the ~ NW-SE segment of the Laxmi Ridge and the Indian subcontinent. There are isolated highs named Wadia Guyot, Panikkar and Raman- Seamounts (Karlapati, 2004; Krishna et al., 2006; Bhattacharyya et al., 2009). On the other hand, the Gop Basin (GB in Fig. 1) lies between the ~ E–W segment of the Laxmi Ridge and the Indian sub-continent. The Eastern Basin,