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Anomalous subsidence on the rifted volcanic margin of Pakistan: No influence from Deccan plume

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ABSTRACT

The role of hotter than ambient plume mantle in the formation of a rifted volcanic margin in the northern Arabian Sea is investigated using subsidence analysis of a drill site located on the seismically defined Somnath volcanic ridge. The ridge has experienced >4 km of subsidence since 65 Ma and lies within oceanic lithosphere. We estimate crustal thickness to be 9.5–11.5 km. Curiously <400 m of the thermal subsidence occurred prior to 37 Ma, when subsidence rates would normally be at a maximum. We reject the hypothesis that this was caused by increasing plume dynamic support after continental break-up because the size of the thermal anomalies required are unrealistic (>600 °C), especially considering the rapid northward drift of India relative to the Deccan-Réunion hotspot. We suggest that this reflects very slow lithospheric growth, possibly caused by vigorous asthenospheric convection lasting >28 m.y., and induced by the steep continent–ocean boundary. Post-rift slow subsidence is also recognized on volcanic margins in the NE Atlantic and SE Newfoundland and cannot be used as a unique indicator of plume mantle involvement in continental break-up.

1. Introduction

The influence of deep-rooted mantle plumes in the formation of rifted continental margins has been long debated (Courtillot et al., 1999). Conventionally, the generation of volcanic rifted margins (i.e. those characterized by sharp continent–ocean boundaries (COB), volcanic seaward-dipping reflector series (SRDS) and thicker than normal oceanic crust) has been linked to the presence of hotter than normal mantle under the incipient rift axis. This asthenosphere melts during extension and adiabatic decompression, thus generating the abundant magmatism seen in these areas (White and McKenzie, 1989; White et al., 1987). Excess mantle heat is often attributed to the presence of a deep-rooted mantle plume, so that volcanic margins and plumes have come to be considered as closely associated. Volcanic margins contrast with non-volcanic, Iberia-type margins where the onset of seafloor spreading is accompanied by little or no magmatism, together with the exposure of mantle rocks at the COB due to low-angle detachment faulting (Pickup et al., 1996; Whitmarsh et al., 2001).

There is however no consensus that a plume or even hot mantle asthenosphere is required to form a volcanic rifted margin (Nielsen and Hopper, 2002). Mutter et al. (1988) invoked the influence of enhanced convective overturn of the asthenosphere underlying the Vøring margin of Norway as a mechanism to drive greater degrees of melting without having asthenospheric temperatures elevated above normal mantle (i.e., about 1280 °C). The sharp COB in this setting is suggested to have accentuated the induced convection caused by plate separation. Similarly Kelemen and Holbrook (1995) proposed that the volcanism seen during the initial stages of oceanic spreading along the eastern U.S. margin is at least partially caused by the presence of anomalously high temperatures under the continent prior to rifting. In this case there is no explicit link to a mantle plume, and higher temperatures could have been achieved due to the insulating effects of the large continental mass prior to break-up (Anderson, 1994).

In this study we present new seismic and well data from the rifted margin of Pakistan in the northern Arabian Sea, as well as its conjugate on the Mascarene Plateau, in order to reconstruct the vertical tectonics since break-up. We use these data to assess the role of hot asthenospheric mantle and plume processes in the formation of this margin. The oldest seafloor spreading in the northern Arabian Sea is dated at ~65 Ma, based on magnetic anomalies (Miles et al., 1998; Royer et al., 2002). The timing and location of this margin segment suggest a link between margin formation and the emplacement of the Deccan Traps flood basalt province, which were also rapidly erupted at this time (Courtillot et al., 1988), and are usually interpreted to be the product of melting from a new plume head striking the base of the Indian lithosphere (Courtillot et al., 1999). White and McKenzie (1989)

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proposed an initial plume head around 1000 km in radius centred on the Deccan continental flood basalts, which places our study area close to the periphery but clearly within the potential influence of plume mantle at the time of break-up (Fig. 1).

2. Data and methods

In this study we employ a combination of both seismic and drilling data from the deep-water Pakistan margin to reconstruct the vertical tectonics of that margin. We further examine the subsidence history of the conjugate Mascarene Plateau using Deep Sea Drilling Project (DSDP) Site 237 (Fisher et al., 1974). Normally the subsidence of oceanic crust follows a predictable pattern, related to cooling and thickening of the mantle lithosphere (Parsons and Sclater, 1977; Stein and Stein, 1992). This standard model can be compared with reconstructions derived from drilling to detect anomalous processes. Oceanic lithosphere formed above a mantle plume will show greater than normal subsidence due to the extra uplift that the plate experiences above upwelling plume asthenosphere. This reflects both the upward flow of mantle at the ridge crest (Ribe and Christensen, 1994), as well as the buoyancy due to the temperature anomaly (Campbell and Griffiths, 1990) and depletion of the mantle peridotite due to melt extraction (Phipps Morgan et al., 1995). Subsequent removal of the margin from over the plume head as a result of plate motion causes faster subsidence than is typical for lithosphere of that age. The classic example of this is the Hawaiian islands (Detrick and Crough, 1978). Analysis of the subsidence of a variety of oceanic large igneous provinces (LIPs) shows that this temporary uplift or "dynamic support" is found in several, but not all regions interpreted to be influenced by plume activity (Clift, 2005). However, dynamic support, along with excess magmatism is a prediction of most standard mantle plume models and its presence is used to infer the influence of plumes.

Our study area is located over a ridge (known as the Saurastra High or Somnath Ridge (Malod et al., 1997)) that is observed as a gravity low offshore the Indus delta. A nearby seismic refraction profile suggests a continental composition, but the line only crosses the edge of the Somnath Ridge and the ray coverage in the lower crust is very sparse (Lane, 2006). The ridge is located between the north of the northern tip of the Laxmi Ridge and the Murray Ridge (Fig. 1). The Laxmi Ridge, which is separated from the Indian sub-continent by the oceanic Gop Rift/ Laxmi Basin, has variously been interpreted as a rifted micro-continental fragment (Bhattacharya et al., 1994; Talwani and Reif, 1998) or a segment of thickened oceanic crust (Pandey et al., 1995). Recent seismic work indicates that the ridge is likely continental, but with a high velocity, underplated magmatic lower crust (Lane, 2006). In contrast, the Murray Ridge (Darymple Trough) represents the active transform boundary between the Indian and Arabian plates (Edwards et al., 2000).

Here we focus on the vertical motions of the basement under petroleum exploration well PAK-G2 (Fig. 1), which seismic data reveal to be located on top of a major volcanic ridge. In addition, we consider DSDP Site 237 on the conjugate Mascarene Plateau. Multichannel reflection seismic data (Figs. 2 and 3) show that the ridge's acoustic basement is marked by a series of volcaniclastic aprons and hyaloclastic deltas, suggestive of explosive volcanism in shallow water depths, and consistent with the earlier identification of subaerially generated SDRS in this region (Gaedicke et al., 2002). The location of the COB on the Pakistan margin is controversial. Clift et al. (2002) argued that the COB is located under the modern shelf, based on restored cross-sections corrected for sediment loading that indicated a sharp COB in that region. In contrast, other studies have indicated a COB located further south, to the SW of the Laxmi Ridge (Talwani and Reif, 1998). Malod et al. (1997) placed the COB at the SW edge of the volcanic ridge, just landward of the first SDRS. DSDP Site 237 is clearly located within strongly attenuated continental crust.

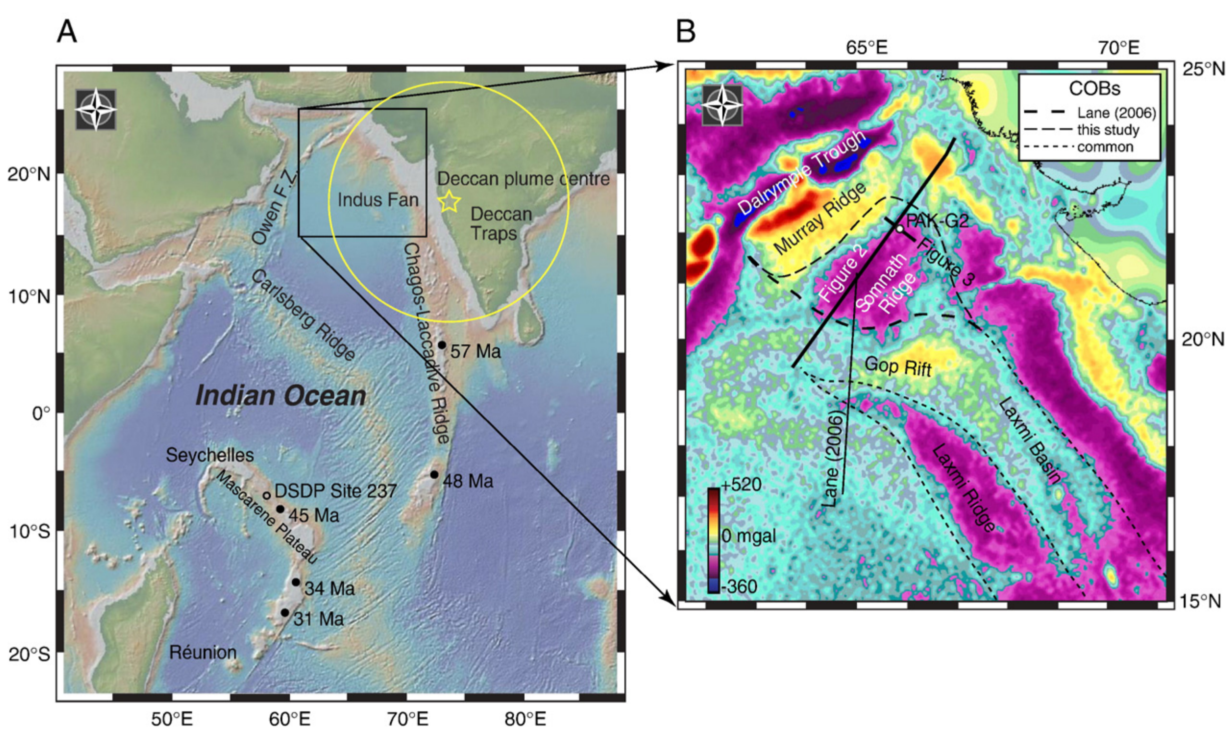

Fig. 1. (A) Shaded bathymetric map of the western Indian Ocean showing the location of the passive margin studied here in relation to the major tectonic features of the region, most notably the Carlsberg Ridge, the Deccan Traps and the Chagos-Laccadive Ridge, representing the proposed track of the Deccan plume, now located under Réunion. Black dots indicate the centre of the plume at different times as reconstructed by Duncan (1990). Yellow circle shows the 1000-km-radius plume head proposed by White and McKenzie (1989). (B) Gravity anomaly map of the margin showing the location of well PAK-G2 on top of a major gravity low representing the thickened crust of the volcanic ridge considered here. Note also the location of the seismic profiles and the refraction profile of Lane (2006). Dashed lines show the locations of the various proposed COBs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).