The role of break-up localization in microcontinent separation along a strike-slip margin: the East India–Elan Bank case study

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Abstract: The Elan Bank microcontinent was separated from East India during the Early Cretaceous break-up. The crustal architecture and rifting geometry of East India and the Elan Bank margins document that the early break-up between India and Antarctica was initiated in the eastern portions of the Cauvery and Krishna–Godavari rift zones, and in the southern portion of Elan Bank. However, the westwards break-up propagation along the Krishna–Godavari Rift Zone continued even after the break-up in the overstepping portion of the Cauvery Rift Zone. Eventually, the western propagating end of the Krishna–Godavari Rift Zone became hard-linked with the failed western portion of the Cauvery Rift Zone by the dextral Coromandel transfer fault zone. Consequently, the break-up location between India and Antarctica shifted from its initial to its final location along the northern portion of the Elan Bank formed by the western Krishna–Godavari Rift Zone. The competition between the two rift zones to capture continental break-up and asymmetric ridge propagation resulted in a ridge jump and the Elan Bank microcontinent release.

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At present, the Elan Bank microcontinent, which is characterized by an east–west-trending promontory, is located inside the roughly north–south-orientated southern Kerguelen Plateau in the southern Indian Ocean, about 900 km to the north of the Antarctic margin (e.g. Coffin et al. 2000, 2002; Wise et al. 2000; Borissova et al. 2003; Gaina et al. 2007) (Fig. 1). It is a relatively positive bathymetric feature in comparison to the surrounding oceanic basin, with a positive free-air gravity anomaly image (see fig. 2 in Coffin et al. 2002). The Elan Bank is currently about 500 m below sea level. It is about 100–200 km wide and 600 km long in the north–south and east–west directions.

The continental nature of the Elan Bank has been indicated by potential field (Coffin et al. 1986; Gaina et al. 2003), seismic (Borissova et al. 2003), seismic velocity (Chavris et al. 1995; Operto & Chavris 1996; Chavris et al. 1997; Chavris & Operto 1999; Borissova et al. 2003) and petrological analyses (Nicolaysen et al. 2001; Weis et al. 2001; Ingle et al. 2002). Petrological analyses were carried out on the fluvial conglomerate samples from the ODP well 1137, which is located in the central part of the microcontinent. The textural, compositional and geochemical analyses of its various clasts confirm the close proximity of the continental crust, which was the primary provenance area (Nicolaysen et al. 2001; Weis et al. 2001; Coffin et al. 2002; Ingle et al. 2002). The isotopic analysis and radiometric dating of clasts suggest that they are sourced from Neoproterozoic and Archaean rocks of the Eastern Ghat Mobile Belt of East India (Weis et al. 2001). All this evidence indicates that the Elan Bank was once attached to East India until its separation, which took place during the Early Cretaceous (Li & Powell 2001; Nicolaysen et al. 2001).

Less is known about the processes resulting in the Elan Bank microcontinent release. Possible analogues for this process include a subgroup in which polyphase rifting and multiple break-up processes led to a ridge jump (Manatschal et al. 2007; Péron-Pinvidic & Manatschal 2010; Gernigon et al. 2012). Another subgroup is associated with hotspot activity leading to a ridge jump. Given the very good data coverage of East India and the reasonable...
coverage of the Elan Bank, it should be possible to derive an exact microcontinent release mechanism here. Furthermore, the role of the strike-slip faulting in the microcontinent release mechanism can also be studied. Therefore, drawing from the interpretation of seismic, well, gravity, magnetic and petrological

Fig. 1. (a) Location map of the study area. The Shuttle Radar Topography Mission (SRTM) topography and bathymetry map (Smith & Sandwell 1997) shows the geographical distribution of different continents, oceanic basins, plate boundaries and physiographical provinces. The East Indian margin, the Kerguelen Plateau and the Elan Bank are highlighted.
data, this study tries to find the release mechanism for the Elan Bank microcontinent.

**Microcontinent development models**

At the beginning of this study, we have two candidate hypotheses explaining the Elan Bank microcontinent release to choose from. They are:

- the plume-refocusing model (see Müller *et al.* 2001);
- the competing rift-zone model (Collier *et al.* 2008; Péron-Pinvidic & Manatschal 2010; Nemčok *et al.* 2012a).

**The plume-refocusing model**

This model requires a mantle plume to assist with microcontinent release, and is built upon an active rift model (Steckler & ten Brink 1986). It shows that the minimum rheological yield strength occurs along the edges of a rifted margin, because the crust there is already weakened and hotter than the normal crust, owing to the conductive heat flow from the adjacent rift (Müller *et al.* 2001).

When the newly formed passive margin moves over a hotspot, it undergoes renewed rifting at the edge of the young margin. Subsequently, the active ridge migrates towards a hotspot, causing the ridge jump to occur as a result of the reheating of the lithosphere due to excess off-axis magmatism (Mittelstaedt *et al.* 2008, 2011). The active ridge jump from the initial spreading axis towards the landwards edge of the continental margin initiates renewed rifting (Müller *et al.* 2001). This isolates the microcontinent, which becomes a part of the newly formed plate. The ridge jump towards the hotspot causes further asymmetry in the oceanic crust accretion. This results in excess accretion and a series of extinct ridges, even within the microcontinent itself (see fig. 2 of Müller *et al.* 2001; Gaina *et al.* 2003 for details).

**Competing rift-zone model**

This model suggests that, during the final stage of rifting, several rift zones simultaneously thin the lithosphere in various places. This results in a coexistence of several weak zones known as crustal wounds (Collier *et al.* 2008; Péron-Pinvidic & Manatschal 2010; Nemčok *et al.* 2012a) (see fig. 4 in Péron-Pinvidic & Manatschal 2010). The competition between crustal wounds, which are prone to hosting the crustal break-up, eventually results in a break-up trajectory by establishing the linkage...
between these rift zones or wounds (Péron-Pinvidic & Manatschal 2010; Nemčok et al. 2012a). The choice of trajectory follows the energy balance principle. The accumulated stress is used for a break-up along a combination of wounds, which requires the least amount of physical work to link and break (see Nemčok et al. 2012b). Once an initial break-up trajectory is established, it is followed by disorganized seafloor spreading. However, depending on the structural, compositional and thermal inheritance and the strain rate, the rifting sometimes does not stop. It further propagates within some of the competing rift zones (Péron-Pinvidic & Manatschal 2010). Such persistent rifting causes the reorganization of the initial break-up pattern. This results in a rearranged linkage of wounds, which represents a final break-up trajectory. As a result, the continental block, which is located between the initial and final break-up trajectories, can become a microcontinent.

Methods

Seismic approach

A number of seismic profiles across the eastern continental margin of India and the Elan Bank were selected to understand the crustal architecture along their contact. They include:

- time-migrated seismic profiles from East India owned by Reliance Industries Ltd;
- time- and depth-migrated seismic profiles from East India acquired by ION Geophysical (http://www.iongeo.com/Data_Library/India/, last accessed on 30 January 2015);
- time-migrated seismic profiles from the Elan Bank acquired by Geoscience Australia.

The Reliance data are a multi-vintage data acquired during the period of 2001–09. The Reliance dataset has an offset of 6–8 km with variable record lengths, ranging from 10 to 12 s two-way time (TWT). The seismic images are good enough for the interpretation of sequence boundaries, top of the basement and crustal architecture. The quality of the combined East Indian imagery is good enough for a regional interpretation and crustal architecture study because of its continuity, dense coverage and depth penetration. The identification of different crustal layers in seismic images follows the general principles discussed by Mooney & Meissner (1992), Meyers et al. (1996), Rosendahl & Groschel-Becker (1999), Odegard et al. (2002), Odegard (2003), Rosendahl et al. (2005), Nemčok et al. (2012a, b) and Whitmarsh & Manatschal (2012).

The ION–Geophysical Indian Span East dataset in the Reliance repository (acquired in 2006) has been used in this study because of its deep imaging capability (see fig. 1 in Nemčok et al. 2012b). It is characterized by an offset of 10 km and a record length of 18 s TWT. The images are in both Pre Stack Time Migration (PSTM) and Pre Stack Depth Migration (PSDM) formats. In the depth domain, the data are available up to a depth of 24–30 km.

The Elan Bank seismic data are represented by a survey named S-179, which was acquired over the Elan Bank and the adjacent part of the Kerguelen Plateau during 1997 by Geoscience Australia (see Borissova et al. 2003). It consists of only seven seismic profiles. Their quality is intermediate and has a record length of 12 s TWT, which is sufficient for crustal interpretation. Some images contain multiples, noise and side swipes.

Gravity approach

The Bouguer gravity anomalies were calculated from satellite-derived free-air gravity data (Sandwell & Smith 2009) and NASA Shuttle Radar Topography Mission (SRTM) bathymetry (Smith & Sandwell 1997). The ship-track gravity data were available only for East India, along several ION–Geophysical India Span profiles. Both gravity datasets were merged together to generate gravity anomaly maps for East India. The Bouguer correction method used slab densities of 2670 and 2200 kg m$^{-3}$ for the onshore and offshore.

Borehole approach

Data from a series of boreholes, particularly biostratigraphic information, have been used to constrain the seismic interpretation of East India. However, the East Indian wells are proprietary. Therefore, their names and coordinates are not listed in this paper. A subset of wells was selected in a systematic matter, relatively evenly distributed over the study area and penetrating maximum possible stratigraphic depths.

The Elan Bank coverage is represented by ODP well 1137.

Synthetic approach

The crustal architecture model of East India and the Elan Bank was developed based on interpreted seismic images. The location of distinct bathymetric change, the geometry of key seismostratigraphic sequences, the presence of rift indicators, the geometry of the rift faults and their detachment depths were used as constraints for defining the crustal architecture model. Our gravity interpretation was used for the calibration of this model.

Seismic profile marriage technique

The seismic profile marriage technique was used to verify the interpreted Elan Bank–East India closing
match. It follows the principles outlined by Rosen-dahl et al. (2005). It was performed for two couples of interpreted seismic-reflection profiles from conjugate margins. The profiles were selected to intersect each other at either oceanic–proto-oceanic or proto-oceanic–continental crustal boundaries. Either their external proto-oceanic ends or external continental ends were matched together. The married profiles were used to test the continuity of the crustal architecture and syn-rift geometry across the contact of conjugate margins. The match was made for the continental break-up time. Any stratigraphic sections younger than the break-up were not considered.

**Tectonic timing determination**

The age markers and palaeo-environment data were used for regional integration and as stratigraphic boundary constraints. The syn-rift and post-rift sequences were differentiated based on changes in their depositional environments and subsidence patterns. The seismic images, together with palynological data, were used to identify the unconformities, condensed sections and sequence boundaries. The interpretation of change in tectonic environments helped us to determine the timing of major events, including continental break-up. The interpretation of available magnetic stripe anomalies and associated fracture-zone geometries, integrated with seismic interpretation, further constrained the determination of the tectonic timing of events.

**Reconstruction**

The initial reconstruction of East India and Antarctica was carried out using global reconstruction models (Reeves & DeWit 2000; Müller et al. 2008; Reeves 2008). Elan Bank was positioned initially using the above-mentioned models only between the East India and Antarctica. The final reconstruction is a derivative of the global reconstruction models constrained by our local data represented by the geometry of crustal boundaries and the distribution of thinned continental, proto-oceanic and oceanic crusts.

**Observations from raw and interpreted data**

**Seismic images**

The brittle upper continental crust in seismic imagery is relatively transparent and has a complex reflector geometry. The lower crust is characterized by high reflectivity and parallel reflectors. The boundary between them is transitional, not following any specific reflector (Fig. 2). Images of the upper-crustal faults are represented by thin zones terminating at the base of the upper crust. Some of them are rather steep and organized in flower structures, others are listric, reaching a flat geometry at the upper–lower crustal transition. Zones of their basal termination are sometimes flat, sometimes undulated, having both convex and concave overall geometries. Images of the upper-crustal blocks between zones of reflector truncations and above the reflective lower crust are characterized by more-or-less isotropic reflector patterns in their deeper parts and parallel ones in their shallower parts.

The Moho is usually well imaged in both continental and oceanic regions, it is represented by a highly reflective zone owing to the higher impedance contrast between the crust and the mantle. The subcontinental Moho is imaged by a bright reflector rising towards the ocean–continent transition (Fig. 2). The oceanic Moho is represented by a bright subhorizontal reflector below the oceanic basement. Apart from specific areas affected by a volcanic addition, where the total thickness reaches values of 7.8–13 km, the thickness of oceanic crust is relatively uniform, having an average of 5.4 km (White et al. 1992). The seismic signature of exhumed continental mantle, referred to in this paper as proto-oceanic crust, is chaotic with multiple discontinuities within the package, with an average thickness of 8.7 km (Fig. 2).

**Gravity images**

By analogy to other passive continental margins, one can observe that there is a major increase in the Bouguer gravity signal near the ocean–continent transition that continues ocean-wards (see Stewart et al. 2000; Bird 2001; Watts 2001; Wyer & Watts 2006; Kusznir 2009; Watts et al. 2009 for comparison). However, free-air gravity images characterize the normal crust of the continental margin by values close to 0 mGal, which increase over the entire margin to positive anomaly landwards of the continent–ocean boundary. Very close to but still landwards of this boundary, the gravity curves undergo a rapid drop to values of about −80 mGal and then steadily climb over a distance of 300–400 km towards values of −30 to −20 mGal. Lowermost portions of these ascending curves contain a prominent hump at numerous East Indian margin segments, imaging the proto-oceanic crust.

The Bouguer gravity data along the Elan Bank profiles indicate several anomaly characters (Fig. 1b). The thickest continental crust landwards of the proximal margin is imaged by a positive anomaly reaching values of 60–80 mGal. The positive anomaly then decreases towards the continent–ocean boundary down to −40–10 mGal on the southern and NW sides of the Elan Bank. Further
ocean-wards it either ascends towards low positive values, as it is the case on the southern side, or it displays a prominent hump before the overall ascending trend takes over, as it is the case on the NW side where the wavelength of this anomaly imaging proto-oceanic crust is about 50 km.

**General crustal architecture and rifting style of the East India and Elan Bank margins**

Different crustal types and their respective boundaries in the six East Indian margin segments, which we adopted here, were already determined in our previous study (see Nemčok et al. 2012b for details). It has been shown that the orthogonal Krishna–Godavari and Cauvery rift zones were hard-linked by the dextral Coromandel strike-slip fault zone. The seismic interpretation and forward gravity modelling confirmed the presence of a proto-oceanic corridor between the oceanic and extended continental crusts. It also has been shown that the width of the proto-oceanic corridor varies along-strike, being wider in front of the orthogonally rifted margin segments and narrower in front of strike-slip-dominated margin segments (Fig. 3). That study already determined the East India margin to be hyper-extended (see Nemčok et al. 2012b for details).

In this study, we observe that the crustal thinning in the Krishna–Godavari Rift Zone took place gradually within the narrow zone coincidental with the continental slope (Fig. 2). Here, the proximal and distal margins are divided by a moderately seaward-dipping break-away fault. The crust thins...
down to zero near the ocean–continent transition within a distance of 160–230 km from the unstretched continental crust (Table 1). The nature of crustal thinning is similar to that in the Cauvery Rift Zone in the south (Fig. 4). The crust there thins down to zero within an average distance of
At the NW margin of the Elan Bank, the crustal architecture is characterized by thinning towards the west (Fig. 5). The crustal thinning takes place over a distance of more than 150 km (Table 2). However, the proximal- to distal-margin architecture cannot be established here, as the seismic profiles do not reach to the interior of the microcontinent. Accordingly, the characteristic break-away faults are also absent. The details of the interpreted tectonostratigraphic boundaries in East India margin are given in Table 3.

In the strike-slip-dominated Pennar–Palar segment of the East Indian margin, the crustal thinning occurs over a very short distance of 60 km (Fig. 6). The proximal and distal margins are clearly divided by the steeply dipping Coromandel Fault. The Coromandel strike-slip fault is characterized by its large offset, across which the bathymetry and sediment accommodation spaces change rapidly. The presence of a series of pull-apart basins towards the distal part of the Coromandel strike-slip fault zone indicates that it was not associated with pure strike-slip but rather with transtension (Fig. 6).

At the southern margin of the Elan Bank, the crust is thinned within a distance of 80 km across a transtensional strike-slip fault system (Table 2). Its main fault acts as the major break-away fault that divides the proximal- and distal-margin architectures (Fig. 7). The steep geometry of the break-away fault suggests that it occurs at the strike-slip-dominated transtensional margin. This observation is in accordance with a presence of negative flower structure that is present further ocean-wards from the break-away fault.

Based on all of the above, one can observe that syn-rift faults are both normal and strike-slip at both conjugate East India and Elan Bank margins. The normal faults control the overall extension, whereas the strike-slip faults act as kinematic linkages between zones of orthogonal extension. The amount of strike-slip v. normal faults indicates that the continental break-up in the Krishna–Godavari and Cauvery rift zones (Nemčok et al. 2012a, b), and the NW margin of the Elan Bank, was dominantly controlled by normal faulting. All these margin segments represent the extensional margins. The normal fault systems at these margin segments gradually become more oblique-slip towards their ends. At the Pennar–Palar margin segment and the southern margin of the Elan Bank, the continental break-up was dominantly controlled by strike-slip faulting. Therefore, these segments represent transform margins.

**Character of the proximal continental margin, decoupled domain**

The proximal Krishna–Godavari margin shows the characteristic features of the aborted H block. The initial H block is the equivalent of a keystone that forms between conjugate normal faults (Péron-Pinvidic & Manatschal 2010). An Aborted H block occurs in failed rifts in proximal margins. The residual H block is characterized by remnants of former H blocks exposed in successful rifted margins that underwent continental break-up (see Péron-Pinvidic & Manatschal 2010 for details). It contains half-graben with thicker sedimentary fill and is bounded by high-angle normal faults (Fig. 8). These faults are detached at mid-crustal levels or near the top of lower crust. They do not offset the Moho. The deformation here is decoupled. The brittle upper continental crust is separated from the brittle upper continental mantle by the ductile lower continental crust, representing a jelly-sandwich model (see Manatschal 2004; Huismans & Beaumont 2005; Manatschal et al. 2007).

The proximal portions of the East Indian strike-slip margins are not very different from these extensional margins. Their faults are also detached at mid-crustal levels and they mostly contain decoupled deformation (Fig. 8). A similar deformation domain at the Elan Bank can be observed only in its central part.

The proximal margins in our study area mainly recorded stretching-related deformation. The brittle deformation is usually located within the upper crust and considerable thinning cannot be observed within

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**Table 1. Width of the different interpreted crustal domains in East India from integrated seismic interpretations and potential field modelling**

| India                  | Proximal margin (km) | Distal margin (km) | ZECM (km) |
|------------------------|----------------------|--------------------|-----------|
| Cauvery Rift Zone      | 80–100               | 40–50              | 60–70     |
| Coromandal strike-slip fault zone | 15–20              | 25–40              | 40–70     |
| Krishna–Godavari Rift Zone | 50–100             | 40–70              | 70–100    |
| North Vizag Transfer Zone | 30–40              | 30–50              | 40–60     |
| Mahanadi Rift Zone     | 60–100               | 60–80              | 60–80     |

ZECM, zone of exhumed continental mantle.
the lower crust. The brittle deformation within the upper continental mantle is not very well imaged. The transition from proximal to distal margin across the break-away faults characterizes the start of the necking domain (see Manatschal et al. 2007; Mohn et al. 2012; Sutra et al. 2013). In this domain, the deformation is generally decoupled, but the crust is considerably thinned and tapered further oceanwards (see also Osmundsen & Redfield 2011).

Character of the distal continental margin, decoupled and coupled domains

The architecture of the Krishna–Godavari distal margin shows features of a residual H block (see Péron-Pinvidic & Manatschal 2010 for the definition). It is characterized by the NW–SE-trending tilted fault blocks of continental basement overlain by relatively thin syn-rift and thicker post-rift strata.
The rift-bounding faults cut through the thinned continental crust. They are detached at the top of the upper continental mantle. The ductile lower continental crust is completely removed as a result of hyper-extension, which is largely controlled by the low-angle ‘concave-up’ detachment fault. The deformation is coupled, characterized by the absence of any ductile layer separating the brittle layers of upper crust and upper mantle. This phase of deformation is related to the thinning phase (see Davis & Kusznir 2004; Manatschal 2004; Manatschal et al. 2007; Reston 2007; Karner 2008; Péron-Pinvidic & Manatschal 2009). However, a small zone of decoupled deformation can be observed in the western part of the distal Krishna–Godavari margin, where lies the transition between the necking and thinning domains. The syn-rift fill in accommodation spaces of the coupled domain has a reduced thickness and does not display any divergent wedges, lacking any larger accommodation space.

The extensional NW margin of the Elan Bank has the characteristics of distal-margin architecture (Fig. 9). It contains a series of distinct, small, tilted fault blocks with very thin, or negligible, sedimentary fill. The boundary between the upper and lower continental crusts is not very well imaged. Despite that, the boundary can be determined using the soling-out depths of the brittle syn-rift faults along a common and relatively flat detachment surface.

Table 2. Width of the different interpreted crustal domains in Elan Bank from integrated seismic and potential field interpretations

| Elan Bank | Proximal margin (km) | Distal margin (km) | ZECM (km) |
|-----------|----------------------|--------------------|-----------|
| NW margin | ?                    | 65–70              | 60–80     |
| SW margin | ?                    | 65–70              | 20–25     |
| Southern margin | 40          | 35–40              | ?         |

ZECM, zone of exhumed continental mantle.
This detachment lies on the top of the lower crust in the eastern part of the basin and the top of the continental mantle further westwards. A prominent reflector below the determined detachment surface in the east is mapped as the Moho surface. The described crustal architecture is typical for distal margins, which contain both coupled and decoupled deformation zones. The entire imaged domain represents a residual H block.

The distal portion of the transform Pennar–Palar margin contains the characteristics of a residual H block, where the crustal thinning is primarily controlled by the Coromandel strike-slip fault zone. However, these characteristics are different from those of extensional margins (Fig. 10). For example, the pull-apart basins associated with transtensional strike-slip deformation contain considerably thicker syn-rift sediments. Another important difference is a thicker lower crust. The major strike-slip faults here cut through the thicker continental crust. They are assumed to be detached at the Moho level. The deformation in the distal margin is decoupled. As the entire crust is thinned down to zero thickness within a short distance and without complete removal of the lower crust, we see almost no coupled deformation domains. A similar situation characterizes the southern margin of the Elan Bank (Fig. 7). This transtensional margin also shows the characteristics of a residual H block.

Character of the proto-oceanic domain

The proto-oceanic domain is characterized by the exhumed continental mantle occurring between the extended continental and oceanic crusts. This domain can be found at both conjugate margins (Figs 8–10). As a result of exhumation, mantle rocks underwent fracturing and alteration owing to the interaction between seawater and peridotite (see Manatschal 2004; Manatschal et al. 2007; Sibuet et al. 2007). The fracturing and serpentinization of peridotitic rocks are responsible for the chaotic and bright reflections in this domain. While the top of the proto-oceanic crust is imaged as a high-amplitude reflector zone, its base does not have any distinct signature. In the Elan Bank and East India, the top of the exhumation domain contains volcanic flows in a few areas. This may be related to the Kerguelen plume activity, which affected the area a bit later.

The reflective top of the exhumation domain represents the convex-up fault (Figs 3 & 8). This fault is responsible for bringing the mantle rocks from underneath a hanging wall and exhuming them at the ocean–continent transition (see Reston 1996; Manatschal & Bernoulli 1998; Manatschal 2004; Manatschal et al. 2007; Tucholke & Sibuet 2007). Because the basin floor in this domain is a fault plane itself, the sediments deposited in this zone were constantly moving along the fault plane as long as its activity continued. At the NW margin of the Elan Bank, a piece of continental block, or extensional allochthon, can be observed. It was detached from the extended crust and moved along the exhumation-controlling fault during the continental break-up process.

The exhumation domain is present along both extensional and transform segments of the East Indian margin (see also Nemčok et al. 2012b). In this study, we found its presence at the conjugate Elan Bank. However, although our study indicates its presence at the extensional NW margin of the Elan Bank, its presence at the transform margin segment remains uncertain.

Character of the oceanic domain

The presence of oceanic crust is best indicated by a relatively flat top basement, parallel to the highly reflective subhorizontal Moho (Figs 3 & 8). This crust is characterized by relatively low-amplitude, high-frequency, subhorizontal and parallel reflectors, and an apparent lack of any internal deformation. Our determined average oceanic

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Table 3. List of interpreted tectonostratigraphic horizons

| Period    | Age/epochs | Horizons | Tectonic events/horizon description                      |
|-----------|------------|----------|----------------------------------------------------------|
| Tertiary  | Early Miocene | T50      | Himalayan Orogeny, drainage reorganization               |
| Tertiary  | Oligocene   | T30      | Major Himalayan Orogeny, basin margin uplift and onset of the monsoon |
| Tertiary  | Eocene      | T20      | India–Eurasia continental collision                      |
| Cretaceous| Maastrichtian | K100   | Deccan volcanism                                         |
| Cretaceous| Turonian   | K60      | India–Madagascar break-up                                |
| Cretaceous| Aptian–Albian | K30     | Top continental break-up (India–Elan Bank)               |
| Cretaceous| Barremian–Hauterivian | K20    | Top syn-rift                                             |
| Precambrian|            | TCB      | Top continental basement                                  |
| Precambrian|            | TLCC     | Top lower continental crust                               |
| Precambrian|            | TCM      | Top continental mantle                                    |
A crust thickness of 5.4 km is similar to normal oceanic crust thickness values of 5–8 km that are documented by experiments and observations at various magma-poor margins (see Mooney & Meissner 1992; Christensen & Mooney 1995; Rosendahl & Groschel-Becker 1999; Rosendahl et al. 2005).

Fig. 6. The NW–SE-trending dip-orientated reflection seismic Profile-5 through the East Indian margin. This is a composite profile, where the SE side is a part of ION profile 880. The profile cuts through the central Coromandal strike-slip fault zone. Note a sharp transition between the proximal and distal margins along a major break-away fault (BAF). A deep basin is also formed adjacent to the main break-away fault. TCB, top continental basement; UCC, upper continental crust; LCC, lower continental crust; TLCC, top of the lower continental crust; POC, proto-oceanic crust; OC, oceanic crust; TOB, top oceanic basement; TCM, top continental mantle. The details of the mapped tectonostratigraphic sequences are provided in Table 3.
The transition between exhumation and oceanic domains in the study area is unclear. It is occasionally characterized by a slight rise of the Moho towards the oceanic domain. This can be observed only in magma-poor segments, such as the southern Krishna–Godavari, Coromandel and Cauvery segments on the Indian side. Unfortunately, volcanic addition to normal oceanic crust is common at conjugate Elan Bank margins, such as the SW margin. The close proximity of the Kerguelen plume is the most likely reason for this phenomenon. Conversely, the southern margin of the Elan Bank to the east of it is characterized by a normal thickness of oceanic crust and very limited volcanic addition.

Interpretation

Tectonic reconstruction of India and the Elan Bank

Initially, we took the present-day physiographical shape of the Elan Bank from the study of Borissova et al. (2003) in this reconstruction. Subsequently, we reinterpreted this shape and associated crustal domains, using seismic and gravity data, arriving at a hyper-extended margin model. While the shape is well constrained at the NW, SW and southern margins, good constraints the for northern and eastern margins are missing.

The initial geometric fit between India and Antarctica, which was achieved using the global plate reconstruction models by Reeves & DeWit (2000), Reeves (2008) and Müller et al. (2008), includes the magnetic anomaly track lines and the rotation poles that were used therein. The Elan Bank was introduced into our model using the same constraints of the above-mentioned global reconstruction models. The initial fit places the Elan Bank in front of the Krishna–Godavari margin segment (Fig. 11). In this tight geometric fit, the NW margin of the Elan Bank fits to the westernmost part of the Krishna–Godavari extensional margin. The western margin of the Elan Bank matches with the Coromandel transform margin. The SE and southern margins of the Elan Bank form a roughly NW–SE trend, which matches with the eastwards continuation of the Cauvery Rift Zone. The southern margin of the
Elan Bank represents a conjugate to the East Antarctica margin, while the northern margin of the Elan Bank matches with the extensional Krishna–Godavari margin. The eastern margin of the Elan Bank roughly matches with the North Vizag transform margin (Fig. 3), connecting the Krishna–Godavari and Mahanadi extensional margins. This Elan Bank margin is apparently limited by the NW–SE-trending pre-existing Precambrian shear zone, which is known as the Nagavali Shear Zone (Chetty et al. 2003) (Fig. 3).

The described initial fit does not account for any hyper-extension at the conjugate margins. It also does not address any timing constraints on the continental break-up. Therefore, we apply regional constraints to this global reconstruction in order to restore and reconstruct the interpreted hyper-extended polyphase rifted margins. These constraints are:

- structural architecture of different margin segments;
- crustal architecture of margin segments and the geometry of crustal boundaries;
- cross-verification with seismic marriage using seismic profiles;
- tectonic timing constraints.

**Structural architecture of different margin segments**

As we move west, the Krishna–Godavari extensional margin gradually becomes oblique before linking with the Coromandel transform margin (Fig. 3). A similar situation exists in the Elan Bank, where the NW margin becomes more oblique as one goes west. Therefore, it is more likely that the Elan Bank closing match with India should place the Elan Bank close to the propagating end of the Krishna–Godavari extensional margin where the rifting style was more oblique.

The interpretation of the northern margin of the Elan Bank can be described as uncertain. This leads to a broad range of possible correlations between it and its Indian conjugate margin.

Based on rifting style, the initial geometric fit can include two alternative placements of the Elan Bank against East India. The first one is the Elan

![Fig. 8. The hyper-extended crustal architecture model of the Krishna–Godavari margin. It shows a proximal margin with stretching-related deformation represented by an aborted H block. The distal margin with mostly thinning-related deformation is represented by a residual H block. Note that the lower crust thins down to zero landwards of the crustal break-up location and the deformation in the distal margin is coupled in comparison to the decoupled deformation of the proximal margin. Further outboard, there is a zone of mantle exhumation and the oceanic spreading domain. ZECM, zone of exhumed continental mantle.](image-url)
Bank fit against the Mahanadi extensional margin between the North Vizag Transfer Zone in the west and the Konark Transfer Zone in the east (Fig. 11). The second option is its placement against the Krishna–Godavari extensional margin bounded by the Coromandel Transfer Zone in the west and the North Vizag Transfer Zone in the east. If we consider rifting style alone, both options appear viable at this stage. Therefore, the correct alternative can be chosen with help of margin segment architecture and geometry of crustal boundaries.

**Crustal architecture of margin segments and the geometry of crustal boundaries**

The Krishna–Godavari extensional margin is characterized by the maximum observed crustal extension (Fig. 3); its width is about 220 km. Determination of width for the Elan Bank conjugate margin is not as accurate owing to limited imaging of the proximal-margin architecture. The best estimate of the distal margin width one can make from the images through the NW margin is about 65 km. If this value is added to the assumed width of the continental core of the Elan Bank, the estimate for the entire margin reaches 100–150 km or more (Table 2). Such an estimate can indicate a highly extended crust, which makes this and the Krishna–Godavari margins similar. These constraints would be in accordance with the Elan Bank placement against the Krishna–Godavari margin segment.

This placement is not exact owing to imperfect restoration of the strongly asymmetric syn-break-up geometry of the conjugates. Despite the potential inaccuracy, the Elan Bank crustal block shifts the oldest continent boundary southwards by about 200–250 km when fitted into the region that contains the transform Coromandel and extensional Krishna–Godavari margin segments.

Apart from the rifting style correlation, the India–Elan Bank match is constrained by the measured width of the exhumation domain. The
exhumation domains are widest where they are adjacent to the extensional margin segments, having an average width of 85 km. The exhumation domains are narrower next to oblique margin and narrowest next to the transform margin segments. An average width of that next to the Coromandel transform segment is 50 km. The widest exhumation domain from the Elan Bank comes from its NW margin, with an average of 70 km. The domain at the Elan Bank is narrower next to the obliquely rifted SW margin and almost absent next to the strike-slip-dominated southern margin. These constraints would be in accordance with the Elan Bank placement against the region that contains the extensional Krishna–Godavari and transform Coromandel margin segments.

Seismic profile marriages

Two East India profiles were paired with two seismic profiles through the NW margin of the Elan Bank to further test our placement of the Elan Bank against the Krishna–Godavari–Coromandel region of East India (Fig. 12a, b). They provide a picture of the conjugate-margin architecture just prior to the final continental break-up.

The widths of interpreted crustal domains (Tables 1 & 2) and conjugate margin crustal architectures in transects indicate that the East Indian margin represents the upper plate. This is because the East Indian margin is located on the hanging-wall side of the convex-up master detachment fault, which is responsible for the mantle exhumation and final continental break-up. The upper plate interpretation is in accordance with its terraced geometry, narrower distal margin width, thicker lower crust, relatively steeper break-away fault and the 'convex-up' geometry of the master detachment fault at this margin.

The conjugate Elan Bank margin represents the lower plate margin. It is characterized by a wider distal margin, a wider coupled domain, a thinner lower crust and a concave-up geometry of the master detachment fault.

As described earlier, the widths of the coupled domains in paired profiles are different. This
Fig. 11. The India–Elan Bank reconstruction. The NW margin of the Elan Bank (NWRZ) ties against the southernmost part of the Krishna–Godavari Rift Zone (KGRZ). As a result, most of the western margin of the Elan Bank (SWRZ) then matches with the roughly north–south-striking dextral Coromandal accommodation zone (CAZ). The SE and southern margins of the Elan Bank fit into a trend along the eastwards continuation of the Cauvery Rift Zone (CVRZ). It is to be noted that the southern margin of the Elan Bank (SRZ) at the present day is a conjugate to the East Antarctica margin. The northern side of the Elan Bank matches with the orthogonally rifted Krishna–Godavari margin. The NE side of the Elan Bank roughly matches with the North Vizag accommodation zone (NVAZ) connecting the Krishna–Godavari and Mahanadi (MNRZ) rift zones. The shape of the Elan Bank is modified from Borissova et al. (2003). ZECM, zone of exhumed continental mantle.
indicates an asymmetry of the extensional system that led to the India–Elan Bank break-up. This margin asymmetry is an indicator of a complex break-up localization, which is a key in understanding the microcontinent release mechanism.

Tectonic timing

The initiation of rifting is well constrained by the age of the oldest syn-rift sediments penetrated by wells at proximal margins. They indicate that rifting started at around the Toarcian (174 ± 1.5 Ma) and continued until the latest Bajocian time (168 ± 1.3 Ma) at different places of the East Indian margin. The events, which followed the initiation of rifting, varied in time and space. For example, the oldest oceanic crust in the Mahanadi Rift Zone (Fig. 3) has a Berriasian age (145 ± 2 Ma), based on magnetic stripe anomalies (see Müller et al. 2008). The presence of magnetic anomaly M11 to the south of Sri Lanka (see Desa et al. 2006) and in the conjugate Enderby Basin of Antarctica (see Ramana et al. 2001; Gaina et al. 2007; Gibbons et al. 2013) suggests that the break-up along the eastern part of the Cauvery Rift Zone and conjugate Antarctica was completed by the Valanginian (136 ± 3 Ma).

Our data indicate that the stretching phase in the Krishna–Godavari Rift Zone took place later than that in the eastern Cauvery Rift Zone. The first confirmed thinning-related deformation here, which is correlated to the onset of the fault block tilting in the coupled domain, started no earlier than during the Berriasian (140 ± 1 Ma) and continued no later than during Valanginian–Hauterivian (132 ± 2 Ma). The end of thinning phase is roughly coeval with the onset of the exhumation phase.

Interpreted lithospheric break-up timing at the transition between exhumation and organized seafloor spreading varies along both the extensional Krishna–Godavari and transform Coromandel margins. The break-up along the western Krishna–Godavari zone, which took place at 123 ± 1 Ma, is slightly younger than that along the eastern Krishna–Godavari zone that took place at 125 ± 1 Ma. The break-up is youngest along the Coromandel transform, where it took place at 120–122 Ma.

Interestingly, based on timing arguments, the Cauvery margin segment must have isostatically felt two break-up events, including:

- the older break-up of Valanginian age (133 Ma ± 2 Ma) that took place in the eastern portion of the Cauvery Rift Zone; and
the younger break-up that took place at around 123 ± 1 Ma in the western Krishna–Godavari Rift Zone.

Geodynamic evolution and release of the Elan Bank microcontinent

The interpreted geodynamic evolution of the Elan Bank microcontinent consists of a sequence of events (Figs 13 & 14).

The initial rifting was characterized by strain distributed over a large region encompassing India–Elan Bank–Antarctica–Australia. Our data suggest that it was initiated during the Toarcian–Aalenian (180–176 Ma). The reconstructed plate setting at 168 Ma shows that the Jurassic rift system contained the Mahanadi, Krishna–Godavari and Cauvery rift zones. The rifting at the Elan Bank was also initiated by this time (Fig. 14a). The initial rifting was accommodated by the stretching phase of deformation. This deformation phase was mainly accommodated by the upper crustal high-angle normal faults occurring in the proximal margins (Fig. 13). These faults served as the basin-bounding faults. During this phase, the rifting was mostly decoupled. Owing to the effect of pre-existing anisotropies, it followed the geometry of the Precambrian mobile belts (Fig. 3).

The stretching phase was followed by the thinning phase. This took place when the broadly distributed extension became localized within narrow zones focused on the future margin segments of East India, the Elan Bank and Antarctica (Fig. 13). During this phase, the deformation started to localize along several major faults (Fig. 13), developing the future necking zones between India and the Elan Bank, and between the Elan Bank and Antarctica (Fig. 13). As mentioned earlier, our tectonic timing observations suggest that the stretching to thinning transition varied in space and time. For example, while the continental break-up was reached in the Mahanadi Rift Zone at about the Berriasian (145 ± 2 Ma), the thinning phase had just initiated in the Cauvery and Krishna-Godavari rift zones (Fig. 14b).

From the middle Berriasian (135 Ma) onwards, the deformation became localized at the edges of relatively stronger lithospheric blocks. A conjugate system of thinning faults between East India and...
Fig. 14. The series of reconstruction (modified from Reeves 2008) shows the geodynamic evolution of the Elan Bank and its separation from East India. The seafloor spreading data come from Müller et al. (2008), the Antarctica COB from O’Brien & Stagg (2007) and the Elan Bank structure is modified from Borissova et al. (2003). TBSZ, terrain boundary shear zone; NVSZ, Nagavalli–Vamshadhara Shear Zone; SCC, Singhbhum Cratonic Complex; BCC, Bastar Cratonic Complex; DCC, Dharwar Cratonic Complex; VC, Vijayan Complex; HLC, Highland Cratonic Complex; RC, S. T. SINHA ET AL.
The future Elan Bank separated relatively stronger lithospheric blocks from their footwall. The intense strain localization was mostly concentrated within the H blocks located in the hanging wall of the thinning faults. This process demarcated Elan Bank as a distinctive strong and relatively less deformed block of crust. The individualization was a primary step towards the creation of the future microcontinent (Fig. 13). However, at this point, it was not decided yet whether it would become a microcontinent or remain as a continental ribbon attached to India.

The interpreted margin architecture indicates that the extension between India and the Elan Bank, and between the Elan Bank and Antarctica, was asymmetric. It is also interpreted that the exhumation process between the Elan Bank and Antarctica started relatively earlier than that between East India and the Elan Bank. Owing to intense strain localization between India and the Elan Bank with continued rift propagation, a new spreading centre was formed between India and the Elan Bank. The older spreading centre between the Elan Bank and Antarctica eventually became deactivated and the active ridge jumped towards the west. During the rift jump, the western propagating end of the Krishna–Godavari Rift Zone was hard-linked with the western portion of the Cauvery Rift Zone. A kinematic linkage was established between the failed Cauvery Rift Zone and the Krishna–Godavari rift zone that underwent continental break-up.

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Fig. 14. (Continued) Rayner Complex; NC, Napier Complex; EB, Elan Bank. (a) The Elan Bank reconstruction in Bajocian times (168 Ma). It shows the initial rifting between India–Antarctica–Elan Bank. The rift signatures at this time indicate stretching phase. Note that the rifts are localized within weak crustal zones. (b) The Elan Bank reconstruction in Berriasian–Valanginian times (140 Ma). This reconstruction shows the initiation of thinning in Krishna–Godavari (KG), Cauvery (CY), Elan Bank (EB) and Antarctica (ANT). The initial seafloor spreading and break-up between the Mahanadi margin segment and Antarctica propagated from the north. Note that rifting continued between Krishna–Godavari Basin–Elan Bank and Enderbyland, and between the Cauvery Basin and Antarctica. (c) The Elan Bank reconstruction at the Valanginian–Hauterivian (132 Ma). Note that the break-up occurred between the Cauvery margin and Antarctica, and between the Elan Bank and Antarctica. A major rift jump occurred in the Krishna Godavari Basin that was associated with a major change in fault geometry and orientation. The Krishna–Godavari Rift Zone continued to propagate westwards. This tectonic regime was characterized by a small amount of stretching. It was mostly thinning-related deformation that localized in the future distal margin. Note a triangular gap between India and Elan Bank at this time. (d) The Elan Bank reconstruction in the Aptian (123 Ma). Note that the break-up occurred between East India and the Elan Bank. Owing to intense strain localization between India and the Elan Bank with continued rift propagation, a new spreading centre was formed between India and the Elan Bank. The older spreading centre between the Elan Bank and Antarctica eventually became deactivated and the active ridge jumped towards the west. During the rift jump, the western propagating end of the Krishna–Godavari Rift Zone was hard-linked with the western portion of the Cauvery Rift Zone. A kinematic linkage was established between the failed Cauvery Rift Zone and the Krishna–Godavari rift zone that underwent continental break-up. (e) The Elan Bank reconstruction in the Albian–Aptian (112 Ma). Active kinematic linkage between different spreading segments was established. The Elan Bank was transferred to the Antarctic Plate and moving away from India. The typical organized seafloor spreading became established in early Indian Ocean. The Coromandel transform activity slowly dies out at this time.
India and the Elan Bank (Fig. 13). The exhumation between the Elan Bank and Antarctica was probably initiated by the Berriasian (close to 135 Ma), while the thinning phase still continued between East India and the Elan Bank. This exhumation phase further contributed to the development of the Elan Bank as either a future microcontinent or a future continental ribbon attached to India.

The continued exhumation between the Elan Bank and Antarctica must have led to the build-up of the asthenospheric anomaly in the future continental break-up location. The passive rise of the magma chamber and the adiabatic melting were assisting with the breaking of the lithosphere, initiating the early oceanization phase. The reconstruction in Figure 14c shows that the early seafloor spreading between the Elan Bank and Antarctica was initiated by the Hauterivian (132 ± 3 Ma).

The East Indian data indicate that the extension between India and the Elan Bank did not cease when Antarctica broke away (Fig. 14c). The eastern Krishna–Godavari zone continued to propagate westwards. The propagation did not stop even after the break-up was reached in the overstepping eastern Cauvery Rift Zone. In addition to the complex lithospheric heterogeneity between East India and the Elan Bank, the intense strain localization can be the result of the slow asymmetric spreading between Antarctica and the Elan Bank. The asymmetric extension helped to localize the strain at the edge of an H block.

Undergoing progressive extension, the lower continental crust in East India and the Elan Bank thinned down to zero at about Hauterivian time (132 ± 3 Ma) in the future continental break-up location. The deformation in the brittle upper crust and brittle upper mantle became coupled and the exhumation fault started to form (Fig. 13). It assisted with the exhumation of the subcontinental mantle along the break-up trajectory. As the extension continued between East India and the Elan Bank, the western propagating end of the Krishna–Godavari Rift Zone eventually became hard-linked with the failed western portion of the Cauvery Rift Zone. It took place through the Coromandel dextral strike-slip fault zone, some time during the Early Aptian (123 ± 1 Ma) (Fig. 14d). The transfer fault linked to the normal fault systems of both rift zones via its northern and southern horstail structures. At that point, an effective kinematic linkage was established between the failed portion of the Cauvery Rift Zone and the Krishna–Godavari Rift Zone, which underwent break-up. The first oceanization and lithospheric break-up must have started by the end of this process, which makes it post-Early Aptian (123 ± 1 Ma). A new spreading centre had been formed between the Elan Bank and East India as a result of continued extension (Fig. 14d).

It is possible that both asthenospheric anomalies – between East India and the Elan Bank, and between the Elan Bank and Antarctica – were simultaneously active for a while, competing for the final continental break-up location by the Early Aptian (123 ± 1 Ma).

The Krishna–Godavari Rift Zone, which did not stop competing, captured the final break-up location in the region to the north of the future Elan Bank microcontinent. The active ridge jumped from the Elan Bank–Antarctica break-up corridor to the Elan Bank–East India break-up corridor (Fig. 14e). The older spreading centre in Antarctica got abandoned as a result of the final break-up localization. At that point, the Elan Bank became a microcontinent and was transferred to the present-day Antarctic Plate though the ridge-jump process.

As the spreading continued in the newly developed northern spreading ridge, Elan Bank started to migrate southwards as a result of a ridge push from the north and continued dextral movement of the Coromandel transform fault system. The Coromandel transform was active for the entire time necessary for the lateral clearance from the contact with the Coromandel transform margin.

By late Albian–Aptian time (112 ± 3 Ma), the Coromandel fault activity was terminated. At this time, the Elan Bank microcontinent was released from its contact with India.

**Discussion**

**The Elan Bank microcontinent in India–Antarctica plate reconstruction models**

The rigid plate models in global reconstructions do not account for the stretched and thinned crust produced by rifting. This omission results in overlaps and gaps in the closing match on top of those caused by the restoration inaccuracies. As a solution to this problem, a determination of the pre-rift extent of the continental crust would be a necessary approach to obtain a meaningful plate reconstruction. Further inaccuracies are potentially associated with the way in which the ocean–continent boundary was determined. Numerous plate tectonic models involving India have used various physical and geophysical markers as proxies for the pre-break-up extent of continental margins. These include the 1000 m isobath (Reeves 2008), the prominent free-air gravity anomaly (Ramana et al. 2001; Subrahmanyam & Chand 2006) and the horizontal gradient of gravity anomalies (Schettino & Scotese 2005).

The palinspastic reconstruction model by Veevers (2009) suggests that a gap to the north of the
16° palaeo-latitude should incorporate the Elan Bank. This gap is also close to the Mahanadi Rift Zone and extends to the northern end of the Krishna–Godavari Rift Zone. This is a possible alternative location where the Elan Bank can be placed. The plate reconstruction of Gaina et al. (2007) also places the Elan Bank into the area in front of the Mahanadi margin segment and the eastern end of the Krishna–Godavari segment. Their interpretation of magnetic anomaly and ridge-jump timing (Gaina et al. 2007) is consistent with our study. It is entirely possible that the alternative location for the Elan Bank in front of the Mahanadi Rift Zone is a viable solution, as our data also indicate a gap there. However, the improved physiographical boundary, the shape of the Elan Bank, the exact determination of the proto-oceanic corridor and the tectonic segmentation of the East Indian margin allow us to fit the Elan Bank further west, close to the Krishna–Godavari segment (Fig. 14) in our local model of the India–Antarctica fit, which is broadly based on plate movement data obtained from Reeves & DeWit (2000). The northern and NW margins of the Elan Bank then match with the proto-oceanic crust–continental crust boundary defined along the entire Krishna–Godavari segment. Such placement is further constrained by data on tectonic timing.

Despite local constraints adding details on top of the global plate reconstruction, this reconstruction contains several gaps. They are potential places where unidentifed microcontinents could have been released along with the Elan Bank during its break-up from East India. Such assumed continental pieces may reside unidentified somewhere in the Indian Ocean or in the Kerguelen Plateau itself (see also Borissova et al. 2002). In fact, the crustal structure of the Kerguelen Plateau could easily include more microcontinents within it, representing a composite microcontinent as mentioned earlier (see Rotstein et al. 2001; Borissova et al. 2002; Bénard et al. 2010).

The role of break-up localization in microcontinent release

The plume-refocusing model. In the Elan Bank case, the plume-refocusing model requires the initial break-up to the south of the Elan Bank to be abandoned in favour of the Krishna–Godavari Rift Zone to the north of it due to the arrival of the Kerguelen plume. This process would be initiated when the India–Elan Bank–Antarctica region was a single plate undergoing extension. First, Antarctica was separated from India–Elan Bank and a new spreading centre was created in between. The approximate timing of its creation is Hauterivian (around 132 ± 3 Ma). A major thermal reorganization took place immediately after the break-up due to the Kerguelen hotspot (Müller et al. 2001; Gaina et al. 2007). A new break-up zone was developed as a result of the thermal instability inside the weak zone, which was already formed between East India and the Elan Bank, during the India–Antarctica rifting and break-up. Continuing rifting in the Krishna–Godavari Rift Zone north of the Elan Bank caused a new spreading centre to develop between India and the Elan Bank. Eventually, the active spreading centre jumped northwards to its new location between India and Elan Bank owing to Kerguelen hotspot interference. This transferred the Elan Bank to the Antarctic Plate. The old spreading centre between the Elan Bank and Antarctica became extinct, and Elan Bank became a microcontinent.

This model includes an active rift model (Turcotte & Emerman 1983), which explains the quick and fast break-up associated with the ridge jumps. The microcontinents and their conjugate margins are expected to have distinct syn-rift and syn-break-up volcanism, as well as major underplating, due to the plume effect. However, these characteristic features are lacking in East India and the Elan Bank. They are also unknown in Antarctica.

The onset of the Kerguelen plume magmatism is recorded by the Rajmahal and Shyellet traps (Baksi 1995; Coffin et al. 2002; Ghatak & Basu 2011). Their locations are 1200–1400 km away from the reconstructed Elan Bank position. The radiometric dating of the Rajmahal volcanics indicates their emplacement at about 117 ± 0.2 Ma (Coffin et al. 2002; Kent et al. 2002; Ghatak & Basu 2011). The offshore portion of the Kerguelen hotspot trail is represented by the 85° E Ridge (Choudhuri et al. 2014). The radiometric dating for this is not available, but the reconstructed plume trail shows that the age near the Mahanadi margin is 112 ± 1 Ma. Underplating has been reported beneath the ridge (Choudhuri et al. 2014), but not much underplating is reported in the rifted zone. All existing data indicate that the underplating and volcanism are post-break-up phenomena, which is also indicated by their younger age in comparison to the age of early seafloor spreading in this region.

The Elan Bank has the crustal architecture of a hyper-extended margin with minimal syn-rift volcanism. Its volcanic rocks are thickest at its SW margin, where they occupy a post-rift position. Their radiometric dating in ODP Site 1137, which penetrates the proximal margin, suggests an age of 107.7 ± 0.5 Ma, representing the peak volcanism (Coffin et al. 2002; Ingle et al. 2002). If the sampling depth of ODP Site 1137 is compared to the reflection seismic imaging (see fig. 3 in Borissova et al. 2003), it lies clearly above the interpreted syn-rift strata.
From all of the above, one can conclude that robust volcanism occurred in the Rajmahal and Shyllet traps and in the Elan Bank at around 118 and 108 Ma, respectively. This is 5 and 15 Ma after our interpreted timing of the break-up between East India and the Elan Bank (123 ± 1 Ma). Therefore, the major plume activity on the Elan Bank has a post-break-up timing.

A similar absence of syn-break-up volcanism is known from several other microcontinent examples, including Jan Mayen (Kodaira et al. 1998), the Seychelles (Collier et al. 2008) and the Lomonosov Ridge (Minakov et al. 2013).

The primary assumption of a plume-refocusing model is that renewed rifting driven by plume refocusing needs a considerable amount of conductive heat transfer. However, several numerical models (Lavier & Manatschal 2006; Simon et al. 2009; Huismans & Beaumont 2011) have indicated that the conductive heat transfer is not sufficient for generating adequate deviatoric stress during rifting. We can conclude that we have found important evidence against the plume-refocusing model of the Elan Bank development, including:

- a lack of significant syn-rift volcanism;
- a lack of significant syn-break-up volcanism;
- a lack of distinct syn-break-up magmatic underplating;
- a presence of hyper-extension-related crustal architecture;
- a break-up v. hotspot volcanism timing mismatch indicating that volcanism came after the ridge jump.

The competing rift-zone model. The Elan Bank natural laboratory has several advantages over other microcontinent examples because of the described high-resolution, dense grid of reflection seismic images providing good control over the crustal architecture interpretation and reconstruction of the rifting history of the India–Elan Bank conjugate margins. The available well data also add to this advantage, with respect to the tectonic timing determination. Evidence in our study suggests that the competing rift-zone model (Collier et al. 2008; Péron-Pinvidic & Manatschal 2010; Nemčok et al. 2012a) is a favourable one for the microcontinent release mechanism in the Elan Bank case. The observations that support this are:

- the hyper-extended margin architecture of East India and the Elan Bank;
- a lack of distinct syn-break-up volcanism;
- the favourable timing constraints;
- the hotspot volcanism timing, which is well constrained by high-precision radiometric dating as occurring post-break-up;
- the interrelation and geometry of the hotspot trail and the Elan Bank drift vectors.

Several numerical modelling studies (Huismans & Beaumont 2005, 2007; Lavier & Manatschal 2006; Simon et al. 2009) selected the competing rift-zone model as being preferable. Studies of the Jan Mayen microcontinent present a case study analogue for such a selection (see Kodaira et al. 1998; Lundin & Doré 2002; Roest et al. 2002; Rey et al. 2003; Scott et al. 2005; Gernigon et al. 2012). In these cases, it turns out that most of the ridge jumps took place during the earliest phase of seafloor spreading, immediately following the break-up and before the spreading patterns become fully organized (Smallwood & White 2002; Rosendahl et al. 2005).

However, ridge jumps are more common when rifting occurs directly above the mantle plume because the active rift migrates in an attempt to remain above the plume, making the rifting easier (Mittelstaedt et al. 2008, 2011).

This discussion indicates that ridge jumps are possible with or without plume refocusing and this study does not represent a universal model but a scenario that took place in the case of the Elan Bank.

The role of strike-slip faulting

The development history of the Elan Bank microcontinent outlined above indicates that four Elan Bank margins underwent continental break-up at different times and completion of its separation from neighbouring plates led to its release. It was the southern extensional and eastern transform margins that started the process, being developed by the Valanginian (136 ± 3 Ma). The former was developed from the eastern portion of the Cauvery Rift Zone, the latter from a portion of the North Vizag transfer fault zone. The key process for the Elan Bank separation was the westwards-propagating break-up along its northern side developed inside the Krishna–Godavari Rift Zone. While the process in the eastern Krishna–Godavari zone was accomplished by 125 ± 1 Ma, the western part underwent break-up by 123 ± 1 Ma. This process was characterized by eastern portions of the rift zone progressively reaching:

- a larger pre-break-up extension of the continental crust;
- a wider corridor of proto-oceanic crust prior to organized spreading;
- a wider corridor of oceanic crust accreted by organized spreading.

This must have caused a slight clockwise rotation of the future microcontinent which led to its final release.

Our data indicate that it was the development of the Coromandel transform fault zone, which represented the remaining fourth side of the Elan Bank still attached to India, that assisted with the last
steps of the microcontinent release. First, the break-up along it took place at around 120–122 Ma, making this Elan Bank margin the youngest of its four margins. Second, its activity assisted in its lateral clearance from any contact with India.

At this point, it would be interesting to look at the kinematic relationship of the Coromandel dextral strike-slip fault zone with both the Cauvery and Krishna–Godavari rift zones. Seismically derived fault patterns of all three structures were published by Nemčok et al. (2012a) in their figure 5b. Their geometries and relationships indicate that the northern end of the Coromandel strike-slip fault zone is represented by a horsetail structure that extends into the normal fault pattern of the Krishna–Godavari Rift Zone. It does this without any cross-cutting of pre-existing normal faults, being directly linked with them. This indicates that the end of the westwards propagation of the Krishna–Godavari Rift Zone must have been immediately replaced by its southwards propagation by changing normal faults to oblique slip faults and, eventually, to strike-slip faults of the dextral Coromandel Fault Zone.

The situation at the southern end of the Coromandel strike-slip fault zone is different. Faults of its southern horsetail structure cross-cut the pre-existing normal fault pattern of the Cauvery Rift Zone. This indicates the arrival of the Coromandel Zone propagation to this region after the development of the controlling faults of the Cauvery Rift Zone.

The earlier discussion unravels the last kinematic steps in the Elan Bank microcontinent release. It was the Krishna–Godavari Rift Zone that developed an overlap with a successful portion of the Cauvery Rift Zone and terminated its westwards propagation by the kinematic linkage with a failed portion of the Cauvery zone via the Coromandel transform. This highlights the fact that the microcontinent release would not have been possible without the development of the Coromandel strike-slip fault zone.

Conclusions

- The Elan Bank microcontinent formation is a result of competing rift-zone propagation and break-up localization along crustal weak zones formed during rifting as a result of hyper-extension. The break-up localization initiated along the two overlapping orthogonally rifted segments and finished along the strike-slip fault zone that represented their linkage.
- The initial break-up between India and the Elan Bank was controlled by continued rift propagation of the western end of the Krishna–Godavari Rift Zone and followed by the Early Cretaceous rift jump from the Cauvery Rift Zone to the Krishna–Godavari Rift Zone.
- The final break-up between India and the Elan Bank was accomplished by the dextral movement along the Coromandel strike-slip fault system. This transform fault system was linked with normal fault systems of both rift zones via its northern and southern horsetail structures.
- The final strain localization occurred as the Coromandel strike-slip fault system was linking the failed western portion of the Cauvery Rift Zone with the western propagating end of the Krishna–Godavari Rift Zone that underwent continental break-up.
- The section of the Krishna–Godavari Rift Zone that did not stop competing with the overlapping Cauvery Rift Zone for the location of the final break-up was able to capture the break-up to the north of the future Elan Bank microcontinent, causing a ridge jump.
- The Coromandel transfer fault system was active for the entire time required for the Elan Bank microcontinent and the seafloor spreading centre to the north of it to clear the contact with the East Indian margin laterally.
- The spreading centre jump occurred as a result of the break-up localization and asymmetric ridge propagation.
- The plume-refocusing model, as an alternative explanation for the Elan Bank release, fails to explain the data. This model explains neither the kinematics of rifting and formation of hyper-extended passive margin nor the ages of all the involved tectonic events. The plume-related volcanism, for example, has post-break-up timing.

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