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Overture for the Mandara and Vasuki Plates

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Abstract Models of past plate motions in the Indian Ocean help map the supercontinent Gondwana and investigate how mantle plumes influence plate tectonics. Reducing confidence in this, however, the range of available models all produce large pre-94 Ma movements, in various kinematic senses, between India and Madagascar. There is no observational evidence for any of these motions, suggesting along with their diversity that they are artefacts stemming from contrasting resolutions of techniques used for reconstructing India and Madagascar to Antarctica. A higher resolution approach to India–Antarctica reconstruction concentrates on geophysical records of relative plate motion azimuths. Applying its results regionally eliminates Indo-Malagasy motions before 94 Ma, and prompts new hypotheses of two small tectonic plates. The early Cretaceous Mandara plate, in the Enderby Basin off East Antarctica, may have initiated and rotated at a mid-ocean ridge that was supplied by excess melt from the Kerguelen plume. The late Cretaceous Vasuki plate may have conveyed Sri Lanka southwards across the western Bay of Bengal. The 85°E and Comorin ridges may have formed at active transform fault zones along Vasuki's margins that were supplied with excess melt from the Crozet and Marion plumes. The model confidently implies the presence of 500,000 km^2 of continental crust beneath the Kerguelen Plateau, places Sri Lanka 1000 km further east within Gondwana than previous reconstructions, and casts doubt on the existence of plate kinematic signals that have previously been attributed to the arrival and spread of the Marion plume beneath India and Madagascar at ~105 Ma.

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1 Introduction and Rationale

Plate tectonic models are valuable contexts for interpretations of many Earth processes and their products. Among these, models of the Indian Ocean can help understanding the shape of Gondwana between its amalgamation around the beginning of the Phanerozoic and its disintegration, which started in Jurassic times (e.g. *Gibbons et al.*, 2013; *Lawver and Scotese*, 1987). They have also contributed to studies of how the motions of lithospheric plates may respond when mantle plumes rise in the upper mantle beneath them (e.g. *Cande and Stegman*, 2011; *Pérez-Díaz et al.*, 2020; *van Hinsbergen et al.*, 2011). If we are to have confidence in these studies, then the reconstructions of plate boundary markers that they are based on should be chosen or built to be accurate at some appropriate resolution. In this work, I examine existing reconstructions of the Indian Ocean through early and mid-Cretaceous times, show why their accuracy might need to be improved, and how this might be achieved by applying higher fidelity observational constraints from those parts of the ocean lying between eastern India and East Antarctica. Using the resulting reconstructions to generate a new plate kinematic model, I go on to describe some consequences for maps of the supercontinent Gondwana and ideas about plume/plate interactions.

At the floor and margins of the Indian Ocean, plate motion is encoded in geophysical and geological markers that reveal the presence of mid-ocean ridges and transform faults, the fracture zones and magnetic polarity reversal anomalies that trace their motions and past locations, and the extended continental margins whose formation preceded them (Figure 1). These constraints are sufficiently well known to recognize two separate chains of divergent plate motions that built the ocean, one each lying west and east of India and connecting its extended continental margins to those of East Antarctica. Today, the western chain records relative motion between plates bearing Africa and Antarctica, which has been accommodated by seafloor spreading at the SW Indian Ridge since Jurassic times (e.g. *Cande and Patriat*, 2014; *Tuck-Martin et al.*, 2018), whilst the eastern chain records relative motion between the same Antarctic plate and a third plate bearing India, accommodated at the SE Indian Ridge (e.g. *Cande and Patriat*, 2014; *Eagles*, 2019). The resultant of these relative motions, between the Indian and African plates, has been accommodated by seafloor spreading at the Central Indian and Carlsberg Ridges since the Paleogene (e.g. *Eagles and Hoang*, 2013).

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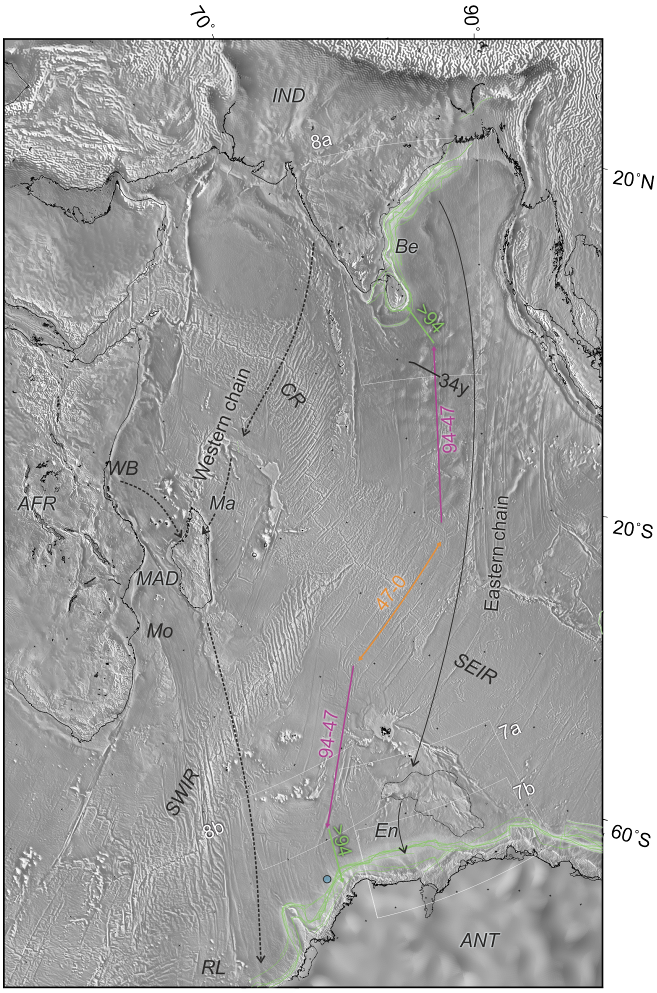

Figure 1 – Satellite-derived gravity anomalies (*Sandwell et al.*, 2014) showing tectonic fabric of the Indian Ocean along the eastern and western chains for reconstructing India (IND) towards Antarctica (ANT). Orange, mauve, green arrows: dated (Ma) segments of eastern chain fracture zones. Blue disk: see captions to Figures 3 and 5. Green lines: interpreted continent-ocean boundaries (*Eagles et al.*, 2015). Black outline: parts of Kerguelen Plateau large igneous province. AFR: Africa; Be: Bay of Bengal; CR: Carlsberg and Central Indian ridges; En: Enderby Basin; Ma: Mascarene Basin; MAD: Madagascar; Mo: Mozambique Basin; RL: Riiser Larsen Sea; SEIR: SE Indian Ridge; SWIR: SW Indian Ridge; WB: West Somali Basin; 34y: magnetic polarity reversal C34y south of India.

Prior to the Paleogene, independent motion of the Indian plate with respect to Africa was accommodated by widening of the Mascarene Basin (e.g. *Eagles and Hoang*, 2013; *Eagles and Wibisono*, 2013). Interpretations of C34y magnetic polarity reversal isochrons from the basin floor show a mid-ocean ridge in the basin was active by 84 Ma (*Eagles and Wibisono*, 2013). Prior to this, the first observable signs of the basin's opening, from its onshore margins, are basalts that erupted at 93–89 Ma along a narrow north striking rift zone (*Cucciniello et al.*, 2022; *Pande et al.*, 2001; *Storey et al.*, 1995; *Torsvik et al.*, 1998). The Mascarene Basin's activity contributed an east–west component of plate motion to the regional plate circuit, such that its onset must have caused transform faults along the ancestral SE Indian Ridge to rotate and generate the ~45° bends observed in fracture zones that lie marginwards of C34y on the ridge's flanks (Figure 1). The distance between C34y and these bends is slightly less than twice the distance between C34y and the next-youngest reversal isochron (C33o; 79.9 Ma). The full rate of seafloor spreading between C34y and C33o was around 80 km/Myr (*Cande and Patriat*, 2014; *Eagles*, 2019). Assuming the spreading rate not to have changed at C34y, and using the relative widths of seafloor produced before and after that time, then the bends might date to ~91 Ma, coeval with the basalt eruptions in the Mascarene rift zone. An oldest plausible date for opening of the Mascarene Basin can be estimated after noting the throughgoing smoothness of the gravity field between the fracture zone bends and C33o, which implies the accretion of oceanic crust did not occur at a full rate of seafloor spreading slower than ~55 km/Myr (*Small*, 1994). Assuming that rate for the production of pre-C34y seafloor, the bends, and with them the onset of Mascarene Basin opening, might at most be as old as ~94 Ma.

The pre-Mascarene Basin history of the western chain is recorded on the flanks of the SW Indian Ridge in the Mozambique and Riiser-Larsen Sea basins off Africa and Antarctica, and in the West Somali Basin between Madagascar and Africa. The eastern chain's early history is recorded in the Enderby Basin off Antarctica. Pairs of solutions for the two chains, generated from studies of these basins and their margins, must be combined in order to investigate the early growth of the Indian Ocean. These combinations invariably impart hundreds of kilometres of pre-94 Ma relative motion between India and Madagascar. This is problematic as there is no geological evidence for any such motion; in fact, the 93–89 Ma basalts of the early Mascarene Basin mark the beginning of the Phanerozoic geological record from the conjugate margins of Madagascar and western India. What is more, despite their large magnitudes, the senses of the calculated pre-Mascarene model motions disagree fundamentally between models. The model of *Gaina et al.* (2007) portrays two opposing-sense phases of transform motion (600 km sinistral followed by 500 km dextral) before and after 130 Ma. *van Hinsbergen et al.* (2021) arrived at a solution showing 300 km dextral transform motion until 135 Ma and 450 km sinistral transform motion afterwards, followed by 200 km of divergence at 105–96 Ma. *Gibbons et al.* (2013) show a single ~300 km phase of sinistral transform motion at 126–120 Ma followed by 170 km of oblique dextral plate divergence until 94 Ma.

Given their great magnitudes and variety of senses, but the absence of a geological record to confirm any of them, the simplest interpretation of all these modelled pre-Mascarene motions is as artefacts introduced by the arithmetic combination of inaccurate rotation parameters calculated for either or both of the eastern and western chains. The next section reviews methods for generating these parameters and their likely inaccuracies, and suggests how they might be improved.

2 Reconstruction Methods and the Source of Suspect Model Motions

Ancient plate motions can be calculated from sequences of static reconstructions, which in turn are built by testing rotations of data that describe displacements of markers observed from ancient plate margins or interiors. Markers from convergent plate boundaries are difficult to use because they tend to be irregularly distributed and suffer multiple episodes of deformation and non-horizontal displacements during their emplacement, and so may support contrasting interpretations of their integrated plate convergent histories (*Cox and Hart*, 1991; *van Hinsbergen and Schouten*, 2021). Divergent plate boundaries, in contrast, generate easier-to-use markers with short, often single-event, structural histories that are readily preserved in the plate interiors by virtue of the outwards displacement of the boundaries they form at. Reconstructions can be built by identifying and fitting together pairs of these markers that have separated after originating along shared boundaries (*Cox and Hart*, 1991; *Eagles*, 2020). The accuracies of such reconstructions can be assessed statistically and/or visually. The intrinsic resolutions of these reconstructions cannot be expected to be finer than the locational errors or uncertainties of their inputs. Among these inputs, previous reconstructions of the Indian Ocean have used correlating pre-breakup-aged rocks, features of extended continental margins, paleomagnetic poles, and seafloor spreading markers.

2.1 Pre-breakup Correlation Reconstructions

The continents surrounding the Indian Ocean preserve evidence for the amalgamation and disintegration of the Meso- to Neoproterozoic supercontinent Rodinia (e.g. *Boger*, 2011; *Shiraishi et al.*, 1994; *Veevers*, 2009; *Yoshida et al.*, 1992) and its Paleozoic successor, Gondwana (e.g. *Kröner et al.*, 2003; *Santosh et al.*, 2014). Some influential reconstructions of the eastern chain have been attempted by identifying, correlating and juxtaposing the boundaries and interiors of distinctive terranes with similar records of these events in India, Sri Lanka and East Antarctica (e.g. *Veevers*, 2009; *Yoshida et al.*, 1992). The youngest, and likely therefore least overprinted and easiest to interpret, structural episode was a period of collisional orogenesis that saw amphibolite and granulite grade metamorphism at ~560–500 Ma (e.g. *Axelsson et al.*, 2020; *Boger*, 2011; *Kröner and Williams*, 1993; *Meert*, 2003; *Veevers*, 2009). Evidence for this metamorphism can be expected to align as the imprint of a continuous ancient orogen or orogens, widely referred to as Kuunga, in any plausible reconstruction of Gondwana.

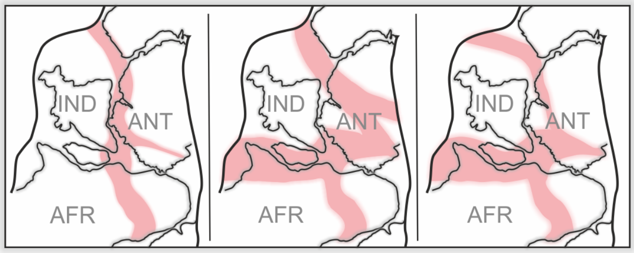

Figure 2 – Contrasting interpretations of the Kuunga and related orogen or orogens (pink) based on distributions of known 560–500 Ma high grade metamorphic rocks, redrawn from *Boger* (2011).

Collisional orogenies can play out over tens of millions of years during which their orogens achieve widths of hundreds of kilometres and develop complex internal structure. Against this backdrop, *Boger* (2011) reviews how detailed variability in sampling and understanding of high grade metamorphic rocks around the Indian Ocean drives debate about the original shape and orientation of the Kuunga orogen or orogens, and discusses three differing interpretations of it drawn from the literature. The existence of this debate implies that even relatively unreworked ancient orogens cannot be expected to deliver definitive paleo-continental reconstructions. Illustrative of this, *Boger* (2011) presents all three orogen interpretations overlain on the same Gondwana configuration (Figure 2).

2.2 Extended Continental Margin Reconstructions

Conjugate pairs of extended continental margins are widely used as constraints for reconstructions. Their outer edges, so-called continent-ocean boundaries, can be understood as the landward, or oldest, edges of the oceanic crust. Together with reconstructions of the seafloor spreading isochrons that lie further offshore, reconstructions of these boundaries can be used to define the azimuth and rate of plate motion during the earliest stages of seafloor spreading. At the extended margins of the eastern chain, *Eagles et al.* (2015) showed interpretations of the continent-ocean boundaries to be subject to ~200 km of combined observational error and interpretational uncertainty. Behind the continent-ocean boundaries lie areas of thin extensionally deformed continental crust. The inner edges of these areas can either be modelled by retro-deforming the continent-ocean boundaries (e.g. *Williams et al.*, 2011) or, as on the eastern chain, interpreted from some signal of or proxy for the often narrow transitions to thicker unstretched crust, the so-called necking zones. These products and interpretations are subject to observational and interpretational uncertainties in the region of ~50-100 km (*Eagles et al.*, 2015), and can be united to generate full-fit reconstructions. Despite these nominal uncertainties, the large set of full-fit reconstructions in Figure 3 shows a similar range (~200 km) of spatial variability as the ensembles of continent-ocean boundary estimates in Figure 1. The useful resolution of eastern chain reconstructions made using extended margin constraints is thus on the order of 200 km.

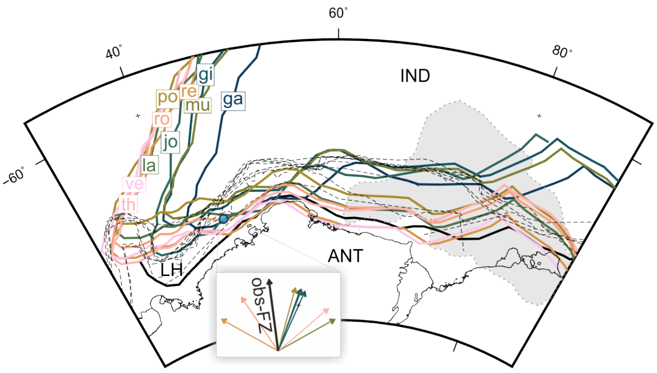

Figure 3 – Selected eastern chain reconstructions using a single Indian necking zone estimate rotated to the Antarctic margin: *Gaina et al.* (2007) (ga), *Gibbons et al.* (2013) (gi), *Jokat et al.* (2021) (jo), *Lawver and Scotese* (1987) (la), *Müller et al.* (2016) (mu), *Powell et al.* (1988) (po), *Reeves and De Wit* (2000) (re), *Royer and Coffin* (1992) (ro), *Thompson et al.* (2019) (th), *Veevers* (2009) (ve). Inset at bottom: unit vectors for early (~130-121 Ma) relative motion directions in the same models compared to fracture zone orientations observed in gravity data at the position of the blue disk (obs-FZ; see Figure 1 for location and gravity data). Dashed lines: Antarctic continent-ocean boundaries of Figure 1. Grey fill: Kerguelen Plateau of Figure 1 positioned arbitrarily for size comparison to the reconstruction ensemble.

Two further factors complicate the use of extended margin constraints on the eastern chain. The first is a large overlap between Sri Lanka and the East Antarctic margin in Gondwana if the island is left fixed in its present-day location with respect to India. Currently, the overlap is eliminated by reconstructing Sri Lanka closer to India, undoing proposed scissor-like extensional opening of the intervening Mannar Basin. Figure 4a summarizes various Mannar Basin reconstructions, mostly built using interpretations and fits of extended margins or Precambrian geological correlations between Sri Lanka and southern India. The second complicating factor is the possible presence of continental crust beneath the Kerguelen Plateau and Elan Bank, the seafloor expressions of a large igneous province that straddles the eastern chain offshore of Antarctica (Figures 1 and 4b). Here, clasts of gneiss, a continental lithology, were cored in a fluvial conglomerate at Site 1137 (*Ingle et al.*, 2002; *Nicolaysen et al.*, 2001), seismic refraction and reflection profiles imaged slow, typically continental, lower crustal velocities and extensional structures in the plateau basement (*Borissova et al.*, 2003, 2002; *Operto and Charvis*, 1995, 1996), and geochemical analyses revealed basalt melt contamination by lower continental crustal material at sites 738, 749, 750, 1137, and 1138 (*Frey et al.*, 2002; *Weis et al.*, 2001). These findings are variously interpreted to support a range of suggested Kerguelen microcontinents (Figure 4b). Amongst them, some authors have concluded that a ~600 km wide Kerguelen microcontinent originated in the Bengal Basin beneath Bangladesh (e.g. *Desa and Ramana*, 2016; *Talwani et al.*, 2016), but others merely that a heavily-extended continental feature underlies Elan Bank whose pre-extensional width is of negligible importance for the fit of the Indian and Antarctic margins (e.g. *Gibbons et al.*, 2013; *Veevers*, 2009).

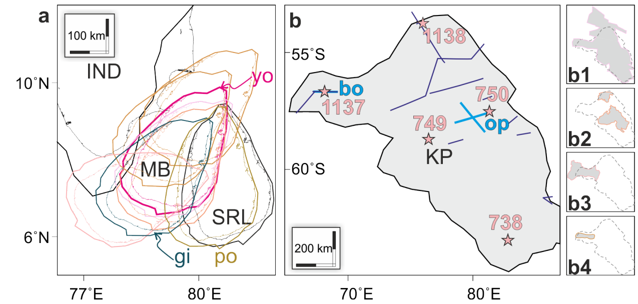

Figure 4 – **a)** Reconstructions of Sri Lanka (SRL) to India (IND) across the Mannar Basin (MB) using paleomagnetic (*Yoshida et al.*, 1992, (yo)) and assumed extended basin margin (*Gibbons et al.*, 2013; *Powell et al.*, 1988, (gi) and (po), respectively) fits. Five further unlabelled fits use pre-Phanerozoic correlations (cf. *Ratheesh-Kumar et al.*, 2020). **b)** Evidence for continental crust at the Kerguelen Plateau (KP; as Figure 1). Stars: Numbered ODP sites where basalts returned continental alteration signatures. Light blue: seismic refraction profiles with slow velocities (*Borissova et al.*, 2002; *Operto and Charvis*, 1995, 1996, (bo) and (op), respectively). Dark blue: parts of seismic reflection profiles with sub-basalt reflections (*Borissova et al.*, 2002). Insets at right: interpreted extents of continental crust (grey) b1: by *Bénard et al.* (2010); b2: by *Talwani et al.* (2016); b3: by *Borissova et al.* (2003); and b4: by *Gibbons et al.* (2013). To help the comparison, the dotted line is the same as the plateau outline from the main part of the figure.

The ~200 km useful resolution of extended continental margin-based reconstructions implied in Figure 3 is larger than the 180–100 km width of the Mannar Basin. The choice of how to move Sri Lanka relative to India by closing the basin is therefore not more important for reconstructing the region than the choice necessary from among the range of interpretations of the shapes of the enclosing Indian and east Antarctic extended margins. A similar argument can be made for some of the smaller proposed shapes of the Kerguelen microcontinent. Using the same observations, it can also be concluded that reconstructions of extended continental margin constraints from the eastern chain are unlikely to offer a useful context for unequivocally interpreting the shapes or original positions of the Sri Lanka or Kerguelen microcontinents.

2.3 Paleomagnetic Reconstructions

Paleomagnetic poles are estimates of the long-term average locations of ancient geomagnetic poles. These estimated locations can be used as constraints on plate reconstructions under the assumption that, like long term averages of today's geomagnetic poles, they coincided with the geographic poles in the distant past. They are determined by using multiple virtual geomagnetic poles (VGPs) to average out the effects of paleomagnetic secular variation. VGPs, in turn, are calculated from magnetization vectors measured in individual oriented rock samples taken from located geological sites. *Meert et al.* (2020) suggest paleomagnetic poles might be deemed reliable in the face of paleomagnetic secular variation if determined from 25 or more reliable VGPs taken in groups of at least three samples from each of eight or more sites. Just two intervals of Jurassic and lower Cretaceous times have supplied paleomagnetic poles from Antarctica (at ~180 Ma) and India (at ~116 Ma) whilst meeting this or a comparable criterion (e.g. *Torsvik et al.*, 2012). Because of this, there are no purely paleomagnetic reconstructions of the Indian Ocean in the pre-Mascarene Basin period.

A single Jurassic–early Cretaceous paleomagnetic pole has been published for Sri Lanka. Its location is consistent with scissor-like opening of the Mannar Basin (Figure 4a; *Funaki et al.*, 1990; *Yoshida et al.*, 1992). The pole was determined using just 17 VGPs from samples taken at a single site on a dolerite dyke. The dyke was not described in detail, but is likely to have been 5–10 m wide (*Arachchi et al.*, 2017). Conductive cooling of dykes this wide is likely to be so rapid (a matter of months (Delaney, 1987)) that their magnetizations sample a tiny fraction of a single cycle (~3000–10,000 years; *Kodama*, 2012) of paleomagnetic secular variation. This leaves it impossible to reasonably assume that the Sri Lankan pole represents a meaningful approximation to the late Jurassic–early Cretaceous geographic pole, other than by chance. Disregarding the pole leaves Sri Lanka's original location in Gondwana constrained merely within the questionable context of low-resolution reconstructions of the eastern Indian and East Antarctic extended continental margins (Figure 3), and the requirement for the microcontinent to adopt a location somewhere along the Kuunga orogen (Figure 2).

2.4 Seafloor Spreading Reconstructions

The highest spatial resolution in reconstructions can be achieved using tectonic and magnetic markers from the oceans. Fracture zones, interpreted from gravity or bathymetric data, and linear polarity reversal isochrons interpreted from magnetic data, locate crossings of ancient mid-ocean ridge systems to well within 10 km (*Müller et al.*, 1991; *Seton et al.*, 2014). Data like these can be used in either least-squares statistical or visual fitting procedures for deriving Euler rotation parameters. These parameters can inform continental deformation and margin configurations by backwards extrapolation to breakup or full-fit times (e.g. *Williams et al.*, 2011). In some cases, they can constrain continental fits more tightly still by interpolation, for instance at propagating divergent plate boundaries (e.g. *Pérez Díaz and Eagles*, 2014) or by summations of rotations in plate circuits (e.g. Eagles, 2019). The statistical techniques allow estimated data location errors to be applied for portraying model reliability as numerical uncertainties in the rotation parameters (e.g. *Chang et al.*, 1990). These typically propagate to, at most, a few tens of kilometres of uncertainty in the locations of reconstructed features, or around an order of magnitude smaller than the corresponding uncertainties in reconstructions derived from extended continental margin or paleomagnetic data.

Seafloor data have been used to generate reconstruction parameters for all the individual legs of the western chain by least-squares (*Cande and Patriat*, 2014; *Eagles and Wibisono*, 2013; *Eagles and Hoang*, 2013; *Tuck-Martin et al.*, 2018) or visual (*König and Jokat*, 2006; *Leinweber and Jokat*, 2012; *Mueller and Jokat*, 2019) fitting of seafloor spreading data. Figure 5 compares three of these models to each other and to the orientation of early relative plate motion that can be observed from fracture zone traces in the western Enderby Basin. None of the model azimuths exceeds 2° divergence from the observed fracture zone orientation. The strong reproducibility of the modelled azimuths over the three studies illustrates the very high resolution of reconstructions that seafloor spreading data support. In contrast, azimuths calculated using eastern chain reconstructions, for which extended margin constraints are more important, universally fail to match the observed fracture zone orientations (Figure 3). Figure 5, conversely, also shows how models based on seafloor data combine to produce, without being predicated on, fits of the conjugate extended continental margins of Africa, Madagascar, Antarctica, and western India. These fits lie comfortably within the wide range of independently proposed margin-based full-fit reconstructions (cf. *Thompson et al.*, 2019). Once mustered, however, they leave a ~750,000 km^2 gap between the eastern Indian and East Antarctic margins (e.g. *Eagles and König*, 2008; *Tuck-Martin et al.*, 2018), and simultaneously close up the smaller gap off Lützow Holm Bay that houses Sri Lanka in extended continental margin-based eastern chain reconstructions (Figure 3). Compared to low-resolution continental margin-based models, this tightly constrained context implies Sri Lanka must have lain further east in Gondwana, together with a continental body that lies veiled beneath the Kerguelen Plateau.

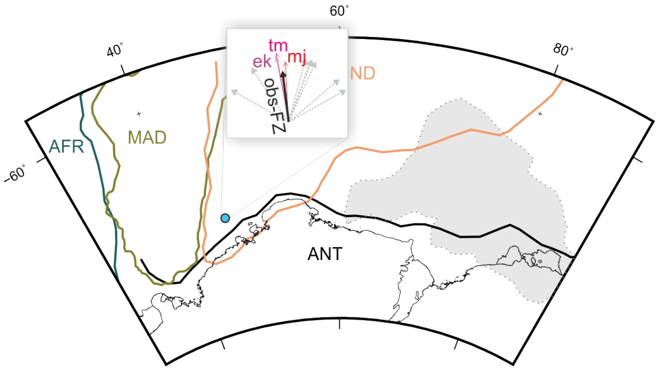

Figure 5 – Implications of western chain solutions for eastern chain assumptions. Background full-fit reconstruction by rotating Africa and Madagascar to Antarctica using the "AAM" and "WSB" rotations of *Tuck-Martin et al.* (2018) and India to Madagascar using a rotation generated for 89 Ma by linear extrapolation beyond the 34y (84 Ma) rotation of *Eagles and Hoang* (2013). Closing the western chain in this way produces a wide underlap further east between the margins of the eastern chain. Grey fill: rotated Kerguelen Plateau as in Figure 3. Inset at top: unit vectors (lengths vary only to aid clarity) for early (~130-121 Ma) relative motion in three western chain models (*Eagles and König*, 2008; *Mueller and Jokat*, 2019; *Tuck-Martin et al.*, 2018, (ek), (mj), and (tm), respectively) compared to fracture zone orientations observed in gravity data at the position of the blue disk (obs-FZ; see Figure 1 for location and gravity data) and to the eastern chain model azimuths of Figure 3 (grey dashed vectors).

2.5 A method for Improved Resolution in Eastern Chain Reconstructions

The previous sections showed why existing eastern chain models should be considered the most likely sources of large errors that manifest as pre-Mascarene Basin motions between India and Madagascar, and why seafloor spreading constraints offer the best chance of modelling the eastern chain more reliably. Previous attempts to use such constraints have focused on magnetic reversal anomaly isochrons (e.g. *Gaina et al.*, 2003; *Gibbons et al.*, 2013; *Royer and Coffin*, 1992). A compilation of global seafloor age estimates (*Seton et al.*, 2020), however, shows that much of the eastern chain's oldest oceanic crust formed during the Cretaceous Normal Polarity Superchron (121–84 Ma in the *Gradstein et al.*, 2020, timescale used here), from which magnetic reversal anomalies are yet to be confirmed. What is more, there is little consensus on the existence, locations, and identities of older isochrons because of sparse coverage by magnetic anomaly profiles of multiple vintages and variable line spacings and orientations. This precludes the possibilities to date the oceanic crust at high resolution and generate sets of Euler rotation parameters for a closely-spaced sequence of reconstructions.

Away from the problem of dating its magnetic reversal isochrons, the eastern chain presents a range of observables that can be used for higher resolution plate reconstructions, via their constraints on the azimuths of relative plate motions (Figure 6). These observables include the orientations of the isochrons, which can be measured on gridded magnetic anomaly maps or by interpolation between neighbouring magnetic anomaly profiles, and used without needing precise knowledge of their age. A global study shows that the great majority (around 90%) of isochrons are oriented to within ±25° of normal to the azimuth of plate divergence and that most of the remaining 10% occur over thin crust formed at ultra-slow spreading rate ridges (*Seton et al.*, 2020). Sheared continental margin orientations constrain relative plate motion azimuths more tightly, to within ~15° (*Mercier de Lépinay et al.*, 2016). More precisely still, *DeMets et al.* (2010) show that the majority of individual transform fault traces in satellite altimeter and multibeam bathymetry data constrain the azimuth with errors of 6° or less, and that these errors together adopt a general normal distribution about a mean of zero, meaning that several such traces should constrain plate motion azimuths more tightly still. Periods of plate motions defined by their azimuths can be dated relative to each other, for instance using stratigraphic or cross cutting relationships, and to volcanic or syn-rift sequences that might be associated with the constraining features. Azimuthal analysis thus promises higher fidelity plate kinematic modelling of the eastern chain, albeit at relatively low temporal resolution.

To analyse azimuth data on the eastern chain, arcs of small circles are plotted about Euler rotation poles, and the poles adjusted until the arcs and the chain's records of relative plate motion azimuths coincide, by visual inspection, within the azimuthal error bounds described above. Here, this workflow was handled in two main ways. Figure 6 illustrates the first, an interactive process using the GPlates small circle tool (*Müller et al.*, 2018). Figures 7 and 8 illustrate the second, using plots of small circle segments produced using GMT scripts (*Wessel et al.*, 2019).

3 Relative Plate Motion Azimuths along the Eastern Chain

Figure 1 shows eastern chain fracture zones that record southwest-directed (since magnetic reversal isochron C21; ~47 Ma) and south-directed (~94–47 Ma) plate divergence, as seen from India (cf. *Eagles*, 2019). Further marginwards, in pre-94 Ma seafloor on the Indian plate, these fracture zones yield to older southeast-striking ones. Their counterparts on the Antarctic plate in the western Enderby Basin strike north-northeast and continue all the way to the continental margin. The inset to Figure 3 shows that extended margin-based eastern chain reconstructions fail to reproduce this azimuth. The corresponding inset to Figure 5 shows that western chain reconstructions, in contrast, predict the traces

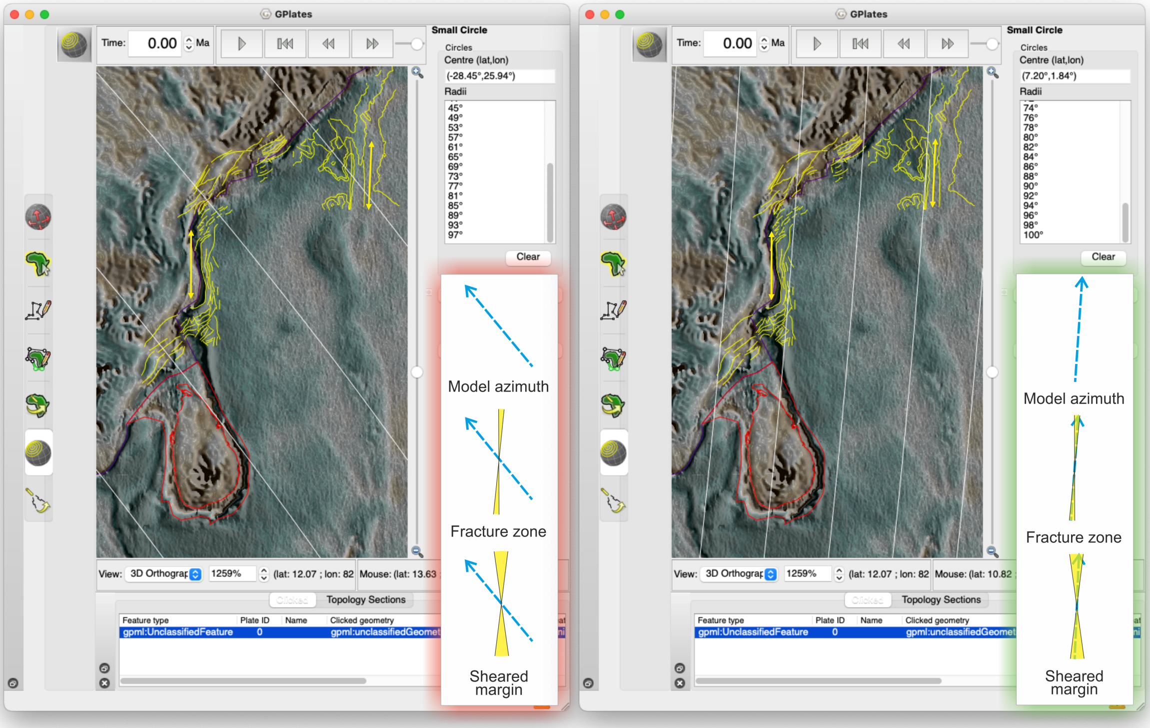

Figure 6 – Use of GPlates small circle tool in western Bay of Bengal. The background image shows altimeter-derived gravity anomalies (*Sandwell et al.*, 2014). **Left:** Small circles (white lines) for an Euler pole ("Centre") at 28.45°S, 25.94°E (calculated for Antarctica in Indian plate reference from *Gibbons et al.*, 2013). Yellow double arrows: relative plate motion azimuths estimated using basement topography contours and fault traces from seismic reflection data (thin yellow lines) along the Indian sheared margin segment and buried strike-slip faults (*Choudhuri et al.*, 2014; *Nemčok et al.*, 2016). **Right:** Same, for Euler pole at 7.20°N, 1.84°E. **Insets:** illustrative visual comparisons of plate motion azimuths implied by the small circles (blue dashed lines) to the sheared margin and fault azimuths, with the confidence envelopes described in the text (yellow).

accurately, as would be expected in the absence of relative motion between India and Madagascar prior to opening of the Mascarene Basin at ~94 Ma.

Figures 1, 7 and 8 show how the gravimetric signals of pre-94 Ma fracture zones fade out completely over seafloor hundreds of kilometres away from the continental margins in the eastern Enderby Basin and in the western Bay of Bengal basin north of Sri Lanka. Comparison of these regions to the Gulf of Mexico, where regional sediment cover is similarly thick or thicker and yet basement fracture zones can be confidently interpreted from gravimetry (*Sandwell et al.*, 2014), suggests the smooth gravity field reflects relatively featureless oceanic basement rather than thick sedimentary cover. The next two sections examine other sources of evidence for relative plate motion azimuths in and around the two basins by examining them in closer detail.

3.1 Eastern Enderby and Shackleton Basins

The eastern Enderby Basin (Figure 7) lies between the Antarctic continental margin and the southwestern edge of the Kerguelen Plateau. Compared to global mean values, its igneous crust is unusually thick (8–12 km) in the north and unusually thin (2–4 km) in the south (*Jokat et al.*, 2021; *Stagg et al.*, 2004, 2005). The basin's short weak magnetic lineations tolerate a diversity of polarity reversal timescale interpretations that have crystallised around the idea of an abandoned mid-ocean ridge crest in the Enderby Basin (*Gaina et al.*, 2003, 2007; *Gibbons et al.*, 2013; *Jokat et al.*, 2021; *Talwani et al.*, 2016). Whilst disagreeing about the ridge's presence, age, and location, all of these schemes are consistent with dates from conjugate volcanic provinces on the Southern Kerguelen Plateau and Indian margin that record a northwards shift of crustal accretion out of the Enderby Basin during the period 118–109 Ma (*Duncan*, 2002; *Kent et al.*, 2002; *Lisker and Fachmann*, 2001; *Ray et al.*, 2005).

Aside from the controversy in identifying them as reversal isochrons, the Enderby Basin's linear magnetic anomalies can be observed to strike west-southwest (e.g. *Gaina et al.*, 2003; *Gibbons et al.*, 2013; *Golynsky et al.*, 2018a), in agreement with predictions of western chain models. Some of the anomalies are paralleled by faint gravity lineaments that accompany dipping reflectors at the top of seismic basement (*Sandwell et al.*, 2014; *Sauter et al.*, 2021). Reflectors like these are widely understood as products of repeated subaerial lava flow episodes at active divergent plate boundaries in igneous or extended continental crust (e.g. *Paton et al.*, 2017). Together, these observations allow an understanding

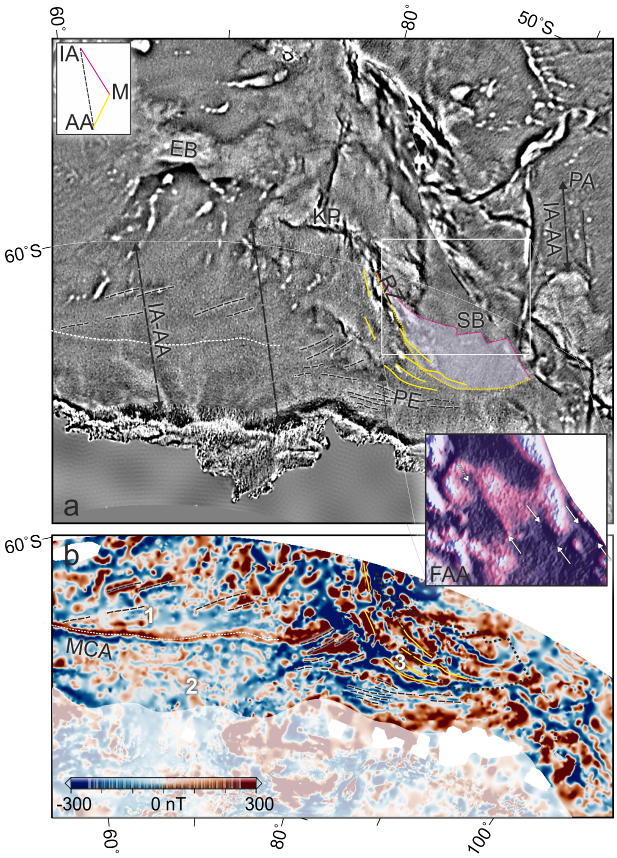

Figure 7 – Enderby Basin and Mandara plate. **a)** Vertical gradient of satellite-derived gravity (*Sandwell et al.*, 2014), with Australian plate reconstructed to Antarctica (*Eagles*, 2019). Black double-head arrows: expected orientation of Aptian Indo-African/Australo-Antarctic (IA-AA) divergence (*Tuck-Martin et al.*, 2018) with Elan Bank (EB) and Kerguelen Plateau (KP) fixed to India. Thick mauve dotted line: abandoned ridge crest in Shackleton Basin (SB). PE: Princess Elizabeth Trough; RZ: Southern Kerguelen Rift Zone. Lilac fill: approximate shape of Mandara plate prior to its extinction. **b)** near surface magnetic anomalies (*Golynsky et al.*, 2018a) showing 1: ENE-trending lineations over thick igneous crust, 2: incoherent field over thin crust, and 3: coherent lineations over normal-thickness oceanic crust in Princess Elizabeth Trough (PE). Black dashed lines: lineations formed during IA/AA divergence. Yellow lines: lineations with obliquity exceeding 25° to IA-AA azimuth. MCA: Mac. Robertson Coast Anomaly (*Stagg et al.*, 2004). Inset top left: sketched relative velocities of Mandara (M), Indo-African (IA) and Australo-Antarctic (AA) plates, for early on during Mandara's motion. Inset middle right: detail of Shackleton Basin free-air gravity anomalies (*Sandwell et al.*, 2014) with arrows highlighting interpreted ridge-transform intersections on abandoned Mandara/Indo-African ridge.

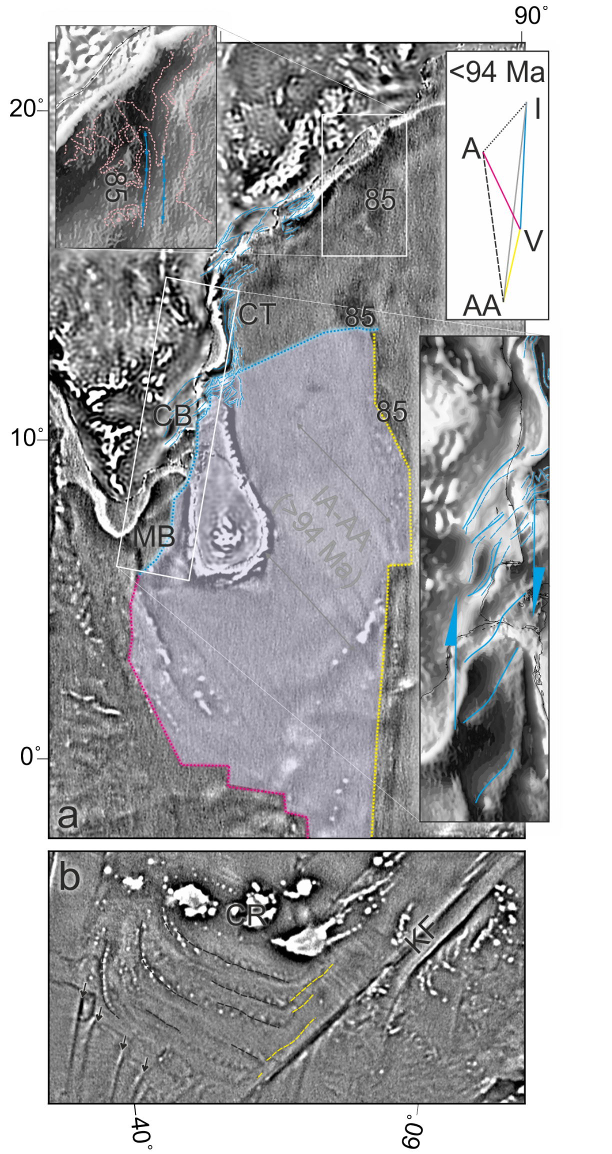

Figure 8 – Western Bay of Bengal and Vasuki plate. **a)** Vertical gradient of satellite-derived gravity (*Sandwell et al.*, 2014) data overlain with faults and basin margins involved in Vasuki/India (blue), Vasuki/Africa (mauve) and Vasuki/Australo-Antarctic (yellow) motion. Lilac fill: approximate area of Vasuki plate just prior to extinction. Grey double-head arrows: expected orientation of pre-Mascarene Basin (>94 Ma) Indo-African/Australo-Antarctic (IA-AA) divergence (*Tuck-Martin et al.*, 2018). Faults on eastern Indian margin from *Nemčok et al.* (2016). **b)** Lineations formed during Africa/Australo-Antarctic (black) and Vasuki/Australo-Antarctic (yellow) plate divergence. CB: Cauvery Basin; CR: Conrad Rise; CT: Coromandel Transform; KF: Kerguelen fracture zone; MB: Mannar Basin. Short black arrows: truncated fracture zones. Inset top left: free-air gravity (*Sandwell et al.*, 2014) detail of northern part of 85°E Ridge (labelled "85") with flanking fracture zone valleys (blue). Pink dashed lines: top seismic basement contours from *Choudhuri et al.* (2014). Inset top right: sketched relative velocities of Vasuki (V), Indian (I), African (A) and Australo-Antarctic (AA) plates. Inset middle right: free-air gravity detail showing transtensional ridges of the Cauvery and Mannar Basins, with faults as in (a) (*Nemčok et al.*, 2016), Cauvery Basin basement ridges from *Watkinson et al.* (2007), and Mannar Basin basement ridges interpreted from base image.

of the eastern Enderby Basin as the product of early Cretaceous Indo-African/Australo-Antarctic plate divergence at a partially emergent and partially submerged divergent plate boundary in receipt of an abundance of melt. Today, melt-rich divergent boundaries are known to manifest as submarine ridges characterized by long-wavelength thermal topography (e.g. the East Pacific Rise), or broader regions of subaerial volcanism (e.g. the Danakil Depression). Both lack the deep (1-2 km), wide (15-30 km) median valleys of less well supplied mid-ocean ridges (*Acocella et al.*, 2008; *Small*, 1994). Once abandoned and left to undergo millions of years of thermal relaxation, melt-rich divergent boundaries can be expected to be characterized by relatively smooth flat basement surfaces, like that observed in the Enderby Basin. Together with the incoherence of the basin's magnetic anomalies, described above, this can explain why the search for magnetic and gravimetric signals of an abandoned ridge crest in the Enderby Basin has not resulted in a consensus.

Figure 7 shows how the Enderby Basin narrows eastwards into Princess Elizabeth Trough, which is floored by a globally typical thickness (~7 km) of oceanic crust (*Jokat et al.*, 2021). Distinct linear magnetic polarity reversal anomalies date the onset of this crust's accretion to ~130 Ma (*Gaina et al.*, 2007; *Jokat et al.*, 2021). The oldest of these anomalies strike within a few degrees of the west-southwest orientation predicted by western chain models for a hypothetical Indo-African/Australo-Antarctic ridge in the Enderby Basin. The obliquity of their younger neighbours to this direction increases offshore, however, until it reaches ~85° in anomalies that mark the flanks of the sparsely-imaged (*Borissova et al.*, 2002) Southern Kerguelen Rift Zone.

Further eastwards still, Princess Elizabeth Trough opens into the Shackleton Basin (Figure 7). *Stagg et al.* (2005) introduce the basin, noting how ~130 Ma and younger magnetic polarity reversal isochrons continue out of the trough and along its southern edge. They present seismic profiles that reveal two modest areas of dipping reflectors set amongst a larger region of smooth-topped acoustically transparent basement over ~7 km-thick oceanic crust. As in the Enderby Basin, these observations suggest accretion of igneous crust by robust melt supply to a divergent plate boundary with both subaerial and submarine segments. Satellite-derived gravity anomalies show that the smooth-topped basement is crossed by three or four long (up to 200 km) northwest-striking basement steps and troughs. Seismic reflection data cross one of the troughs (at shot points 4800-5000 on profile GA-229/22 of *Stagg et al.*, 2006), revealing a crust cut through by steep faults that suggest the trough and related northwest-striking features formed at transform fault zones. The orientations of these zones differ by 18-23° from the Indo-African/Australo-Antarctic divergence azimuths predicted by western chain models for Aptian (~121–113 Ma) times. Individual segments of an abandoned mid-ocean ridge between the faults can be tentatively interpreted in gravity anomaly data.

3.2 Western Bay of Bengal Basin

Magnetic anomalies along profiles crossing the western Bay of Bengal basin have been interpreted to demonstrate either the absence or the presence of linear polarity reversal isochrons dating from various stretches of Cretaceous time but are too incoherent to support a more detailed consensus (e.g. *Desa et al.*, 2006; *Gaina et al.*, 2007; *Gibbons et al.*, 2013; *Rao et al.*, 1997; *Talwani et al.*, 2016). The 350 km-long Coromandel transform lies at the basin's western margin (Figure 8). Its ~75 km wide north-striking crustal necking zone, steep basement faults and deep pull-apart basins (*Ismaiel et al.*, 2019; *Nemčok et al.*, 2016) are characteristic of a continental margin segment formed in north-south oriented shearing (cf. *Mercier de Lépinay et al.*, 2016).

Figure 8 shows how the steep faults of the Coromandel transform splay southwards into the Cauvery Basin. The splays border NE-striking sigmoidal sub-basins that experienced dextral transtension (*Chand and Subrahmanyam*, 2001; *Dasgupta*, 2018; *Nemčok et al.*, 2016). The sub-basin margins raise gravity anomalies that run uninterrupted southwards into the neighbouring Mannar Basin. Although these anomalies have been interpreted in terms of an axial ridge or graben in a divergent Mannar Basin (*Desa et al.*, 2006), their continuity suggests that the transtensional sub-basins of the Cauvery Basin are the northern parts of a ~790 km-long north–south oriented train of such basins whose southern half underlies the Mannar Basin. Based on cored, seismic reflection-, and outcrop-based constraints on their tectonostratigraphies, the Cauvery and Mannar basins both experienced protracted or two-phase opening histories with a first phase beginning in late Jurassic to early Cretaceous Indian/Antarctic divergence and a second ending in less well defined tectonic contexts as recently as Turonian-Santonian (94–84 Ma) times (*Baillie et al.*, 2002; *Nagendra and Nallapa Reddy*, 2017; *Narasimha Chari et al.*, 1995; *Premarathne and Ranaweera*, 2021; *Premarathne et al.*, 2016; *Watkinson et al.*, 2007). Apatite and zircon fission track analyses from Sri Lanka record a long-lived history of extensional fault activity with similar peaks in early and mid-Cretaceous times (*Emmel et al.*, 2012).

The 85°E Ridge runs as a chain of buried volcanic basement highs along the eastern edge of the western Bay of Bengal basin (Figure 8). *Desa et al.* (2013) summarize a literature that is broadly concerned with the relative importance of volcanic and plate boundary processes in the ridge's development. More recently, deep reflection seismic profiling across the basement high at ~11°N revealed two summits that are separated and bounded by steep faults, some cutting the entire crust, situated below steps and valleys at the top of acoustic basement (*Shang et al.*, 2022). Those authors interpreted the relationships in terms of late Cretaceous volcanism along an active transform fault. Another deep profile across the segment at ~17°N shows a similar pair of summits with bounding faults, steps and valleys (*Desa et al.*, 2013), inviting a similar interpretation. A dense grid of shallower seismic data over this segment (*Choudhuri et al.*,

2014) reveals two of the basement valleys, east of the eastern summit, to be linear ~250 km-long north-trending features, each ~20 km wide (Figure 8). *Choudhuri et al.* (2017) related these features to a history of lithospheric flexure under loading by the 85°E Ridge, but this mechanism does not easily explain the presence of two valleys or the indifference of their strike to a wide gap in the ridge at 16°N, where the load vanishes. Instead, the relief more closely resembles that formed by the actions of a pair of closely-spaced strike-slip faults, consistent with a transform fault zone interpretation. The strike of the valleys implies the transform fault zone would have accommodated south-directed plate motion relative to India.

4 Results: A New Plate Kinematic Model

Figure 8 presents evidence for southwards plate motion relative to India in the western Bay of Bengal that contradicts earlier model predictions of southeast-directed early Cretaceous Indo-African/Australo-Antarctic plate divergence there. The discrepancy prompts the hypothesis of a previously unsuspected third plate in the western Bay of Bengal. In Figure 7, the azimuthal misfits of the Southern Kerguelen Rift Zone and of transforms along the abandoned ridge crest in the Shackleton Basin to the expected orientations of the crest of, and transform offsets along, an Indo-African/Australo-Antarctic ridge are large enough to prompt the hypothesis of a fourth plate. The shapes of these plates' remnants are interpreted on the basis of basement features revealed in geophysical data in Figures 7, 8 and 9. The plates are named Vasuki and Mandara after figures in Samudra Manthan, the story of another ancient Indian ocean. Figure 9 summarizes a new plate kinematic model that contextualizes the two plates. The model can be examined using a GPlates project (*Eagles*, 2023), or in the Supporting Movie.

As well as plate motions, interpreted plate boundaries, plate boundary products, and continental outlines, the new model depicts motions of the Kerguelen (post-149 Ma), Crozet (post-100 Ma) and Marion (post-95 Ma) hotspots. Mantle plumes are thought to experience slow advection with the mantle they ascend through, imparting a modest component to the relative motion of the plates and the hotspots at their summits. In recognition of this, the GPlates project can show three alternative sets of locations for its three hotspots. One ignores advection, assuming all plume conduits to be fixed within an undeforming mantle (*Müller et al.*, 1993). The other two attempt to account for advection, modelling it using similar approaches but differing data sets for the migration of the conduit summits and differing mantle convection and plate motion models (*Doubrovine et al.*, 2012; *O'Neill et al.*, 2005; *Steinberger and Torsvik*, 2008). The resulting differences between the fixed and moving hotspot locations lie in the range 500–800 km, consistent with the expected magnitudes of the effects of advection and the uncertainties involved in modelling it. Figure 9 shows the hotspots only using the fixed model (*Müller et al.*, 1993), both for clarity and because it achieves acceptable long-term proximity of the hotspots to their supposed products at the Kerguelen Plateau and around Madagascar.

The new model starts in Jurassic—early Cretaceous times with plate divergence north and south of Australia, which forms part of a single plate together with Greater India, and further west between west Gondwana, bearing Africa, and east Gondwana, bearing India and Antarctica. The divergence north of Australia and Greater India excises a continental sliver referred to as Argoland (*Gibbons et al.*, 2012) whose remnants are preserved today in the eastern Tethyan collision zone of southeast Asia (*Advokaat and van Hinsbergen*, 2024). The model is not intended to show the detailed post-rifting histories of the various parts of Argoland. To the south, the divergence causes around 500 km of separation of Australia's southern shelf from Antarctica, forming deep sedimentary basins on the shelves and broad magnetic quiet zones further offshore (*Totterdell et al.*, 2000). Unlike in previous reconstructions that portray this separation as the very slow onset of the Australian plate's still ongoing separation from Antarctica (e.g. *Gibbons et al.*, 2012), the new model depicts it as a discrete ancient phase (*Eagles*, 2019) of divergence between the Greater India and East Gondwana plates (Figure 9a) that ended in early Cretaceous times. The Greater India/East Gondwana boundary continues westwards between peninsular and Greater India, its remnants perhaps cropping out today as some of the Jurassic MORB-like ophiolites known from the Tibetan Plateau (*Qian et al.*, 2020). Southwest of it, the East Gondwana/West Gondwana boundary runs through the West Somali, Mozambique and Riiser-Larsen Sea basins. The basins' development is portrayed using the Euler parameters of *Tuck-Martin et al.* (2018), with a ridge jump detaching a microcontinent at Beira High in the Mozambique Basin, after *Mueller and Jokat* (2019).

The Greater India/East Gondwana boundary is abandoned at 130.6 Ma when a new boundary, running orthogonally to the old one but accommodating plate divergence along a very similar azimuth, splits East Gondwana and Greater India through the Gascoyne, Cuvier and Perth Abyssal plains (*Williams et al.*, 2013), Princess Elizabeth Trough (*Jokat et al.*, 2021), and the Shackleton and central Enderby basins (Figure 9b). The model development of this new boundary north and east of the Cuvier Abyssal Plain is closely based on that of *Gibbons et al.* (2012). Over and south of the Cuvier Abyssal Plain, the model uses western chain rotation parameters from *Tuck-Martin et al.* (2018) together with ridge jumps adapted from *Gibbons et al.* (2013) and *Gibbons et al.* (2012) to excise the Quokka Rise

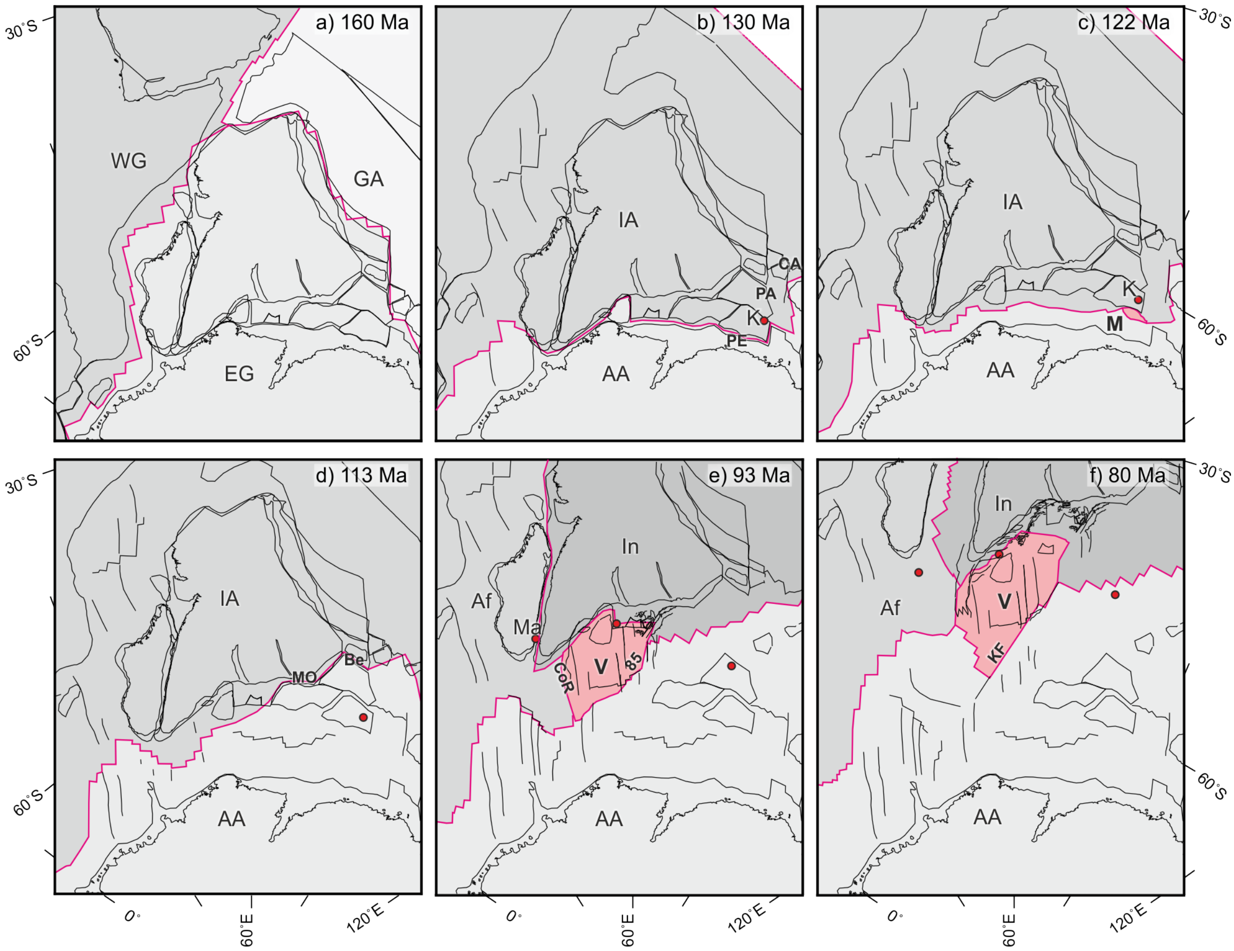

Figure 9 – Reconstructions, present-day Antarctica fixed, with sketched plate boundaries and selected continental shelf edges, coastlines, extinct ridges, and fracture zones. AA: Australo-Antarctic plate; Af: Africa plate; EG: East Gondwana plate; GA: Greater India-Australia plate; IA: Indo-African plate; In: Indian plate; M: Mandara plate; V: Vasuki plate; WG: West Gondwana plate. Red dots: approximate locations of the Kerguelen (K), Crozet (C), and Marion (Ma) plume heads (fixed mantle reference frame). Other features mentioned in text: Be: Bengal Basin; CA: Cuvier Abyssal Plain; CoR: Comorin Ridge; MO: Mahanadi Offshore basin; PA: Perth Abyssal Plain; PE: Princess Elizabeth Trough; 85: 85°E Ridge.

and Zenith and Wallaby plateaus from the west Australian margin. Instead of the western Enderby Basin, the new boundary continues westwards via the Cauvery and Mannar basins, leaving India fixed together with Madagascar within an Indo-African plate on one side and Sri Lanka fixed within an Australo-Antarctic plate on the other. The basins are only briefly active in this setting, which initiates their northeast-striking basement ridges (Figure 8) as the footwalls of normal faults. Soon afterwards, the locus of plate divergence jumps south of Sri Lanka into the western Enderby Basin, fixing it to the Indo-African plate, at 129.4 Ma. The Mandara plate grows in the Shackleton Basin at 127–114 Ma (Figure 9c). Subsequently, Indo-African/Australo-Antarctic plate divergence continues at a long boundary that relocates northwards to abandon the Enderby Basin by 113 Ma. At 94 Ma, the Indo-African plate splits along the line of the Mascarene Basin, forming separate Indian and African plates, around the same time that the Vasuki plate forms and moves in the western Bay of Bengal east of India (Figure 9e). After 80 Ma, the Vasuki plate and its margins are abandoned (Figure 9f) and the model shows the onset of a period of relative motions of separate Australo-Antarctic, Indian, and African plates.

4.1 The Mandara Plate

The Mandara plate is integral to the history of the divergent plate boundary that originated between the Australo-Antarctic and Indo-African plates at ~130.6 Ma. Before Mandara, the boundary initiated in the Shackleton Basin and southern Princess Elizabeth Trough, developing into a mid-ocean ridge producing normal thickness (~7 km) oceanic crust (Figure 9b) (*Stagg et al.*, 2005). Further west, in the central and eastern Enderby Basin, the ridge was magma-starved and produced thin oceanic crust. Anomaly M5n (~128 Ma) marks the boundary to unusually thick crust produced all along the ridge, which presumably started to interact with the Kerguelen plume that the fixed-hotspot reference frame of Müller et al. (1993) places just to the east. In Princess Elizabeth Trough, M5n is also the first of the unusually oblique (>25°) isochrons that may document the addition of lithosphere to the Australo-Antarctic plate at its boundary with the Mandara plate (Figure 6; *Golynsky* *et al.*, 2018a; *Jokat et al.*, 2021; *Stagg et al.*, 2005). Starting with M5n, successive isochrons lengthen towards the northwest, in which direction their obliquities also increase seawards to as much as 85°at the Southern Kerguelen Rift Zone. The change illustrates northwestwards growth of the Mandara plate by propagation of its boundary with the Australo-Antarctic plate towards their shared Euler pole near the rift zone's northwestern tip. Mandara's oceanic setting, abundant melt supply, and near-pole rotation are reminiscent of a class of small plates that form and grow between overlapping ridge segments near active hotspots (e.g. *Hey et al.*, 1985). The model shows Mandara's motion ceasing at 114 Ma.

After 114 Ma, the stretch of Australo-Antarctic/Indo-African boundary that had previously hosted Mandara relocates northwards into the Kerguelen Plateau. Its brief action in this location slightly separates the plateau's southern part from its central part and Elan Bank along parts of the 77 Degree Graben and Labuan Basin (Figure 9; *Borissova et al.*, 2002). By 113 Ma, the ongoing northward relocation places the Australo-Antarctic/Indo-African boundary further north in the Mahanadi Offshore and Bengal basins (Figure 9d), where its action is witnessed by dyke intrusion and eruptions of basaltic magma (*Kent et al.*, 2002; *Lisker and Fachmann*, 2001; *Ray et al.*, 2005). As these basins open, they detach Elan Bank and the Southern Kerguelen Plateau from India (Figure 9e). The plateau, abandoned Enderby and Shackleton basins, and the Mandara plate and its boundaries consequently all become passive features within the Australo-Antarctic plate.

4.1.1 Mandara: Model Uncertainties

The remnants of the Mandara plate today lie between the South Kerguelen Rift Zone and the abandoned Indo-African/Mandara mid-ocean ridge in the Shackleton Basin. The plate is small and much of its floor post-dates the onset of the Cretaceous Normal Polarity Superchron, leaving no clear magnetic isochron fabric. The details of the Mandara plate interpretations in the GPlates model must thus be understood as very speculative. The ~128 Ma onset of the model Mandara plate's motion is based on the excess obliquity of the Australo-Antarctic plate's M5n isochron in Princess Elizabeth Trough. Globally, albeit rarely, even larger obliquities are known from active mid-ocean ridges (Seton et al., 2020), leaving it possible that Mandara started moving later than 128 Ma. The depicted cessation of motion at 114 Ma is put at the young end of the 119–114 Ma range of dates for breakup related volcanism from the Indian margin (*Kent et al.*, 2002). However, a different range of dates (118–109 Ma) that might be related to this episode has been reported from the Kerguelen Plateau (*Duncan*, 2002). Considering both ranges, the Mandara plate's maximum lifespan may have been somewhere between 5 Myr shorter and 5 Myr longer than the model portrays.

4.2 The Vasuki Plate

The boundaries of the model's Vasuki plate localize east of India at 94 Ma, capturing pre-existing lithosphere, including Sri Lanka and some of the seafloor east and south of it, from the Indo-African plate. Further west, 92–89 Ma volcanism in Madagascar records the early stages of breakup of the Indo-African plate into separate African and Indian plates over the Marion plume and along the line of the Mascarene Basin (*Storey et al.*, 1995; *Torsvik et al.*, 1998). Southwards, around the same time, and perhaps as a consequence of its interaction with the Marion plume, the segmented African/Australo-Antarctic ridge in the northwesternmost Enderby Basin evolves by ~91 Ma into a single long curved ridge. This leaves a set of prominently truncated north-striking fracture zones at the southern margin of a basin marked by arcuate abyssal hills and chains of seamounts (Figures 8b, 9e).

The eastern tip of the new, curved, African/Australo-Antarctic ridge hosts the Vasuki/Africa/Australo-Antarctica triple junction (Figure 9e). The Vasuki/Africa plate boundary runs northwest from the triple junction along the Comorin Ridge. The Vasuki/Australo-Antarctic plate boundary runs northeast from it along the Kerguelen Fracture Zone and southern part of the 85°E Ridge. The Vasuki/India plate boundary runs along the northern part of the 85°E Ridge. The Comorin and 85°E ridges each strike oblique to the relative motions they accommodated, consistent with their interpretations in recently acquired seismic data as 'leaky' transform fault zones supplied with excess melt from the Marion and/or Crozet plumes (*Pandey et al.*, 2022; *Shang et al.*, 2022). West of the 85°E Ridge, the India/Vasuki boundary continues as a mid-ocean ridge across the western basin of the Bay of Bengal. The lack of basement expression of a fossil median valley at this ridge implies that it too was well supplied with melt from one or both plumes. After meeting the eastern Indian margin further west, the boundary turns southwards along the Coromandel transform before splaying out to form the Cauvery–Mannar transtensional basin complex, reactivating the NE-striking extensional faults that had first formed in the early Cretaceous fragmentation of East Gondwana (Figure 8b). The model Vasuki plate ceases to move independently at 80 Ma.

4.2.1 Vasuki: Model Uncertainties

The model Vasuki plate's total motion, as seen in the Indian reference frame and depicted in the GPlates project, is about 825 km. It is not currently possible to reliably subdivide this relative motion into stages because of the absence of reliable identifications of magnetic reversal isochrons in the western Bay of Bengal basin. The uncertainty in this value can be estimated to 100–200 km, based on the sum of uncertainties involved in visually fitting crustal necking zones interpreted from two pairs of 50–100 km wide continental shelf edge gravity anomalies, one each north and south of the island to their Indian and Antarctic conjugates. The uncertainty in the modelled motion azimuth is within 15° of the strike of the Coromandel transform, and within 6° of the strike of strike-slip faults near the 85°E Ridge, or a maximum of ±108 km across the strike of the Coromandel sheared margin.

The modelled motion onset is chosen based on Turonian (94-90 Ma) dates of localized uplift and late syn-rift sedimentation in the Cauvery and Mannar basins and basalt volcanism in the Mannar Basin that may have occurred in response to crustal thinning over Marion plume-affected mantle (*Nagendra and Nallapa Reddy*, 2017; *Narasimha Chari et al.*, 1995; *Premarathne and Ranaweera*, 2021; *Watkinson et al.*, 2007). A pre-Turonian onset would require strong northwest-southeast directed divergence on the Vasuki/Australo-Antarctic plate boundary at the Kerguelen Fracture Zone because of the north-south orientation of India's motion with respect to Australo-Antarctica as part of the Indo-African plate at that time. Gravity data do not suggest that any products of such divergence exist (Figure 8b), so 94 Ma is likely to be a reliable maximum age. Cessation dates much earlier than 85 Ma would have seen the Vasuki plate move faster than Antarctica southwards away from India, implying convergence at its southern margin, for which there is also no evidence. A latest cessation date is more difficult to constrain using available data from the basins, but may not have been much later than 15 Myr after onset given that the smooth basement of the western Bay of Bengal basin implies seafloor spreading rates did not drop below about 55 km/Myr. The 80 Ma date used in the GPlates model was chosen to coincide with a local plate boundary reorganization shortly after chron C33o, which saw part of the Africa/Antarctica ridge just north of Conrad Rise abandoned (Tuck-Martin et al., 2018) and prominent transform faults appear along the India/Antarctica ridge (*Eagles*, 2019).

In summary, as seen from India, the GPlates project's Vasuki Plate moves by 825 km over a period of 14 Myr, at an average rate of 59 km/Myr. Uncertainties on these estimates might allow for total motion of the real Vasuki plate to have been as little as 625 km or as much as 1025 km, and its longevity to have been as short as 9 Myr, or as long as 15 Myr.

4.3 Microcontinents in Gondwana

The model shows three microcontinents detaching from the margin of eastern India. The largest underlies the Kerguelen Plateau and detaches starting at 114-113 Ma by northward relocation of the Indo-African/Australo-Antarctic plate boundary into the Indian continental margin (Figures 4b and 9). Figure 10 shows where, south of the scattered evidence for continental crust, a long refraction profile over the plateau's southern edge indicates the presence of a simple, thick, three-layered, seismically fast crust, typical of an oceanic large igneous province (*Jokat et al.*, 2021). The mixed overall picture of continental and oceanic crust beneath the plateau is consistent with the geochemical interpretations of basalt contamination at various drill sites by a mixture of in situ continental lower crust and locally detached plugs of continental lower crust entrained in convecting upper mantle beneath a narrow young ocean basin (*Frey et al.*, 2002; *Weis et al.*, 2001). The former interpretation seems appropriate for sites 749, 750, 1137, and 1138, all of which lie along seismic profiles with evidence for continental layers, and the latter for site 738, which lies on the seismic refraction profile of *Jokat et al.* (2021) over thick igneous crust.

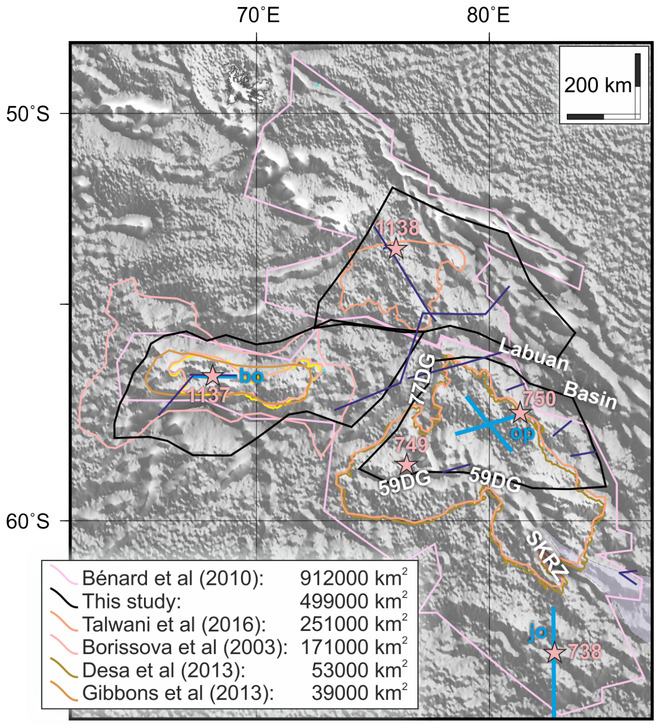

Figure 10 – Interpretations of the Kerguelen microcontinent and its present day area (*Bénard et al.*, 2010; *Borissova et al.*, 2003; *Desa et al.*, 2013; *Gibbons et al.*, 2013; *Talwani et al.*, 2016) overlain on present-day satellite-derived gravity anomalies (*Sandwell et al.*, 2014). Blue lines as in Figure 4b plus seismic refraction profile of *Jokat et al.* (2021) (jo). 77DG: 77 Degree Graben; 59DG: 59 Degree Graben; SKRZ: Southern Kerguelen Rift Zone (all from *Borissova et al.*, 2002). Lilac fill: body of Mandara plate as in Figure 7.

The Kerguelen microcontinent outline in Figures 9 and 10 is interpreted on the basis of the cored and geophysical constraints and an assumed requirement to completely populate the full-fit reconstruction of the eastern chain with continental crust. The full-fit context is defined by the western chain rotations of *Tuck-Martin et al.* (2018), which offer a reliable spatial resolution of a few tens of kilometres. The dominating uncertainties are therefore those expected in interpreting the edges of the microcontinental blocks and their Indian and Antarctic conjugates for applying the rotations to (cf. *Eagles et al.*, 2015). Among these, interpretation of the northern conjugate pair is likely to be more challenging because of burial of the Indian continental margin beneath the Neogene Ganges Delta and prograded Eocene shelf edge (*Alam et al.*, 2003), and deformation and volcanic modification of parts of the Kerguelen Plateau's northern edge during and since its Paleogene breakup from Broken Ridge (*Borissova et al.*, 2002; *Rotstein et al.*, 2001). Further south, the Antarctic margin appears structurally simpler each side of a short prograded segment off Prydz Bay (*Huang et al.*, 2022). Its conjugate is suggested to lie along the southern edge of Elan Bank and its eastwards prolongation along the 59 Degree Graben. The interpreted microcontinent covers an area of half a million square kilometres, towards the larger end of the range of previous interpretations.

The model's most familiar microcontinent is Sri Lanka, which is proposed to have detached from the Indian margin as part of the Vasuki plate at ~94 Ma. Figures 9 and 11 show the island originating east of Antarctica's Napier Peninsula, around 1000 km further east in Gondwana than the location in Lützow Holm Bay that was first suggested ninety years ago (*Du Toit*, 1937) and has been conventional for longer than the last fifty (e.g. *Gaina et al.*, 2007; *Gibbons et al.*, 2013; *Jokat et al.*, 2021; *Lawver and Scotese*, 1987; *Powell et al.*, 1988; *Reeves and De Wit*, 2000; *Royer and Coffin*, 1992; *Smith and Hallam*, 1970; *Veevers*, 2009). Its context is a gap between the restored East Antarctic and eastern Indian continental margins that is defined on the basis of seafloor spreading data implying uncertainties on the order of a few tens of kilometres. With this, the gap is significantly resolved, in contrast to the ~150 km-wide gap off Lützow Holm Bay that is merely permitted by extended continental margin reconstructions with their uncertainties of ~200 km (cf. Figure 3). Figure 11 shows how the new location for Sri Lanka also permits reconstruction of a plausible continuous segment of the Kuunga orogen. The microcontinent's dispersal from this eastern location with respect to India is, furthermore, recorded at higher azimuthal resolution (<15° from the orientation of the Coromandel margin segment and <6° from the orientation of strike-slip faults at the 85° East Ridge) than the plausible range of published 'scissor-rift' interpretations of the Mannar Basin (~45° in the ensemble of Figure 4a).

The smallest microcontinent, named here Chandra, is signalled today by a gravity low of around -50 mGal centred on 83.5°E, 11.5°N, and reconstructs to between two comparable lows on the eastern Indian continental rise (Figure 11). Like Sri Lanka, Chandra is shown as detaching from the Indian margin as part of the Vasuki plate, albeit slightly later at 91 Ma. The Chandra microcontinent is a new and tentative interpretation, which need not be inconsistent with the previous attribution of the gravity anomaly to an isolated volcanic centre (*Choudhuri et al.*, 2014).

5 Discussion

The new plate kinematic model for the Indian Ocean reconciles the testimonies of the eastern and western chains for the first time by carefully prioritizing choices of methods and data for the best achievable precision on the eastern chain. It is the first model of the region to avoid artefactual plate motions between or within India and/or Madagascar, and thus the most consistent with their shared geological record. In this section, I use the model as the basis for a discussion of interactions between buoyant plumes arriving and ascending in the upper mantle, and the lithosphere above them.

5.1 Arrival of the Kerguelen Plume

The earliest (~147-130 Ma; *Olierook et al.*, 2017; *Zhu et al.*, 2009) possible igneous products of the Kerguelen plume appear at the intersection of the newly formed Indo-Africa/Australo-Antarctic plate boundary and its Greater India/East Gondwana predecessor before and during their changeover. The new boundary is later elaborated on near the plume by the addition of the Mandara plate. Occurrences of younger plume-related rocks occur successively further north of Mandara after its abandonment, first in association with the rift-affected interior of the Kerguelen microcontinent (*Coffin et al.*, 2002) and later within the Mahanadi Offshore Basin and the neighbouring Indian continental interior (*Kent et al.*, 2002; *Lisker and Fachmann*, 2001). Taken together, these observations are consistent with the idea that divergent plate boundaries and plumes in the upper mantle appear to influence each other to maintain mutual proximity over long periods, which *Whittaker et al.* (2015) related to mechanisms of extraction of large volumes of melt from plume mantle. *Olierook et al.* (2019) noted that the early Kerguelen melt products associate with the Kuunga orogen. The orogen is likely to have been a site of relatively enhanced gravitational potential since the thickening of its crust during Gondwana's amalgamation, suggesting that the range of proposed regional interactions between plumes and divergent plate boundaries also includes gravitational interactions with potential rift zones.

5.2 Arrival of the Marion Plume

van Hinsbergen et al. (2021) proposed the existence of a ~10,000 km long active pre-Mascarene African/Indian plate boundary running northwards from between the conjugate margins of Madagascar and India into, and then across, the now-subducted Neotethys Ocean north of Greater India. They proposed that the Marion plume's ascent and spread beneath the southern part of this boundary applied

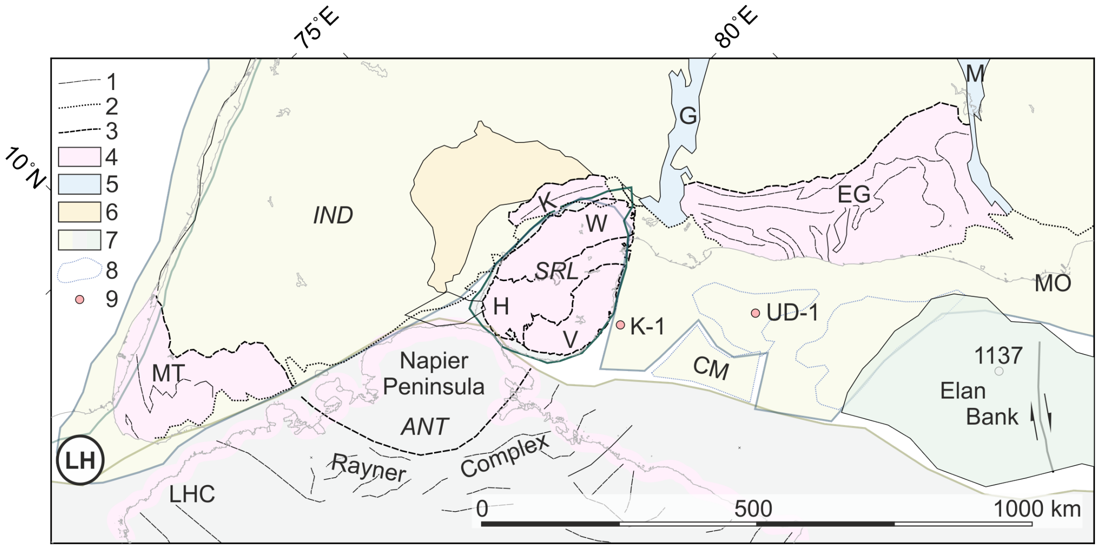

Figure 11 – Fit reconstruction in present-day India reference frame. 1: structural trends in selected terranes, in Antarctica from magnetic anomalies (*Golynsky et al.*, 2018a), in India after *Wandrey* (1998) and *Axelsson et al.* (2020), and in Sri Lanka after *Kröner et al.* (2003). 2: inland edges of Cauvery and Mahanadi Offshore (MO) basins. 3: selected geological boundaries between and to units with Kuungan metamorphic ages (EG: Eastern Ghats Terrane; H: Highland Complex; K: Krishna Province; LHC: Lützow Holm Complex; MT: Madras and Trivandrum blocks; V: Vijayan Complex; W: Wanni Complex). 4: Units with Kuungan metamorphic ages (*Axelsson et al.*, 2020; *Meert*, 2003; *Veevers*, 2009). 5: Late Paleozoic-Mesozoic Godavari (G) and Mahanadi (M) basins. 6: Cuddapah Basin (late Proterozoic). 7: Undifferentiated or unexposed basement. 8: Prominent offshore negative gravity anomalies interpreted as indicative of continental basement including Chandra microcontinent (CM). 9: Wells K-1 and UD-1 that bottomed in "Precambrian basement" (*Krishna et al.*, 2016). 1137: Drill site 1137 with 'Kuungan' biotite ages in fluvial conglomerate clast (*Nicolaysen et al.*, 2001). Elan Bank fault from (*Borissova et al.*, 2003).

traction forces at the bases of the African and Indian plates, rotating them apart about an Euler point a little north of Madagascar. North of this point, they noted that the same rotation would require the two plates to have converged, and that traction forces related to plume arrival could thus explain the emplacement of ophiolites in Oman and Pakistan and the onset of western Neotethyan subduction in the 105-96 Ma period. Although *van Hinsbergen et al.* (2021) described how the northern parts of their long plate boundary might be considered more likely than alternative Neotethyan plate boundary schemes (e.g. *Jagoutz et al.*, 2015; *Müller et al.*, 2016), they did not address the lack of any geological evidence for pre-Mascarene plate divergence further south. This divergence, by 200 km, of a pair of 1500 km long conjugate margins, obliges the appearance of at least 300,000 km^2 of new and/or modified surface area, whose complete absence from the geological record is very difficult to attribute to lack of preservation or insufficient data.

The new model presented here was not built to directly reconstruct any lost intra-Tethyan plate boundaries but can help discriminating between existing suggestions for them. Its divergent Indian/African plate boundary initiates by ~94 Ma at the earliest, and does not evolve from any earlier boundary. The boundary's Euler rotation pole lies ~9000 km away to the north, and so requires the complete length of any potential northward continuation into and across the Neotethys region also to been divergent. The age and kinematics of such a boundary thus both leave it impossible to regard it as a plausible general setting for emplacement of the western Neotethyan ophiolites. It is simplest instead to conclude that no Indian/African plate boundary existed in Neotethys prior to 94 Ma.

If an Indian/African plate boundary setting for subduction onset in the western Neotethys is to be ruled out as a complication that is unnecessary for understanding the development of the Indian Ocean, then the related notion of the Marion plume as a source of tractions that were significant enough to perturb the motions of two major lithospheric plates should be regarded as unproved. Beyond this conclusion, the 2 Myr delay between the onset of divergence at the new model's Indian/African plate boundary and eruption of the first Marion plume melt products is far shorter than the 10-15 Myr period during which numerical simulations suggest that plumes ascending the upper mantle might apply divergent tractions before impacting the base of the lithosphere (*van Hinsbergen et al.*, 2011; *Wang and Li*, 2021). What remains, as seen also with the Kerguelen plume, is a more general association between a plume, its melt products, and parts of one or more divergent plate boundaries, in this case those of the Mascarene Basin and, potentially, some of those around the margins of the Vasuki Plate.

6 Coda

Uncertainty, manifest as calculated but geologically undocumented early to middle Cretaceous plate motion between India and Madagascar, has plagued global and regional plate kinematic models for decades. The model presented here, which does not produce any such motion, was built by careful consideration and prioritization of the resolving powers of available constraints on past plate kinematics in the eastern Enderby and western Bay of Bengal basins. It also introduces two small plates, Mandara and Vasuki, to explain evidence for plate motion azimuths in the basins that existing major plate motion models fail to reproduce. For these reasons, the model should be considered the most accurate available depiction of plate kinematics in the early opening of the Indian Ocean, and a more reliable context for understanding the roles the growing ocean played in the Earth system than its predecessors. It might be tested, and replaced in the future, if targeted acquisition of geological samples and geophysical data from the Enderby and western Bay of Bengal basins result in better dating of the timing of tectonic and magmatic activity along the proposed margins of the Mandara and Vasuki plates, and help refine the still very coarse estimates of the extent of continental basement beneath the Kerguelen Plateau.

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Data availability

The new GPlates project (*Eagles*, 2023) is available from the Zenodo repository under CC-BY: Creative Commons Attribution 4.0 International (CC-BY-4.0) license: http://dx.doi.org/10.5281/zenodo.10353154

The GPlates interactive software, used to help develop and visualize the plate kinematic model, is available via the reference cited here as GPlates (2023). This work used version 2.2, for which the source code can be found at https://sourceforge.net/projects/gplates/. GPlates is released under GNU General Public License version 2.0 (GPLv2).

The Supporting Movie was built using ffmpeg tools, available via the reference cited here as *FFmpeg* (2024). This work used version N-108433-g8089fe072e-tessus. Source code can be found at https://git.ffmpeg.org/ffmpeg.git. ffmpeg is licensed under the GNU Lesser General Public License (LGPL) version 2.1.

The ADMAP2 compilation of near-surface magnetic anomaly data in Antarctica (*Golynsky et al.*, 2018b) used for analysis of the Enderby Basin in the study, is available from the PANGAEA repository under Creative Commons Attribution 3.0 Unported (CC-BY-3.0) license.

The version 32 global free-air gravity and vertical gradient of gravity anomaly data (*Sandwell et al.*, 2014) used for analysis of the Enderby and western Bay of Bengal basins in the study are available via the link in the reference. No licence information is available.

The Generic Mapping Tools (GMT) geospatial mapping and analysis software, used to help develop and visualize the plate kinematic model and for preparing all of the figures except figures 2 and 5, is available via the reference cited here as GMT (2023). This work used version 5.4.5. GMT is released under GNU Lesser General Public License and the source repository is at https://github.com/GenericMappingTools/gmt

Competing interests

The authors declare no competing interests.

Peer review

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