1 Oceanic microplate formation records the onset of India-Eurasia collision

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7

8 Abstract

9 Mapping of seafloor tectonic fabric in the Indian Ocean, using high-resolution satellite-derived vertical
10 gravity gradient data, reveals an extinct Pacific-style oceanic microplate ('Mammerickx Microplate') west of
11 the Ninetyeast Ridge. It is one of the first Pacific-style microplates to be mapped outside the Pacific basin,
12 suggesting that geophysical conditions during formation probably resembled those that have dominated at
13 eastern Pacific ridges. The microplate formed at the Indian-Antarctic ridge and is bordered by an extinct
14 ridge in the north and pseudofault in the south, whose conjugate is located north of the Kerguelen Plateau.
15 Independent microplate rotation is indicated by asymmetric pseudofaults and rotated abyssal hill fabric,
16 also seen in multibeam data. Magnetic anomaly picks and age estimates calculated from published
17 spreading rates suggest formation during chron 21o (~47.3 Ma). Plate reorganizations can trigger ridge
18 propagation and microplate development, and we propose that Mammerickx Microplate formation is
19 linked with the India-Eurasia collision (initial 'soft' collision). The collision altered the stress regime at the
20 Indian-Antarctic ridge, leading to a change in segmentation and ridge propagation from an establishing
21 transform. Fast Indian-Antarctic spreading that preceded microplate formation, and Kerguelen Plume
22 activity, may have facilitated ridge propagation via the production of thin and weak lithosphere; however
23 both factors had been present for tens of millions of years and are therefore unlikely to have triggered the
24 event. Prior to the collision, the combination of fast spreading and plume activity were responsible for the
25 production of a wide region of undulate seafloor to the north of the extinct ridge and 'W' shaped lineations
26 that record back and forth ridge propagation. Microplate formation provides a precise means of dating the

onset of the India-Eurasia collision, and is completely independent of and complementary to timing constraints derived from continental geology or convergence histories.

Keywords: microplate, extinct ridge, pseudofault, Indian Ocean, India-Eurasia collision, plate reorganization

1 Introduction

Satellite gravity data have been used for decades to map major tectonic structures on the seafloor, on a near-global scale (e.g. Matthews et al., 2011; De Alteriis et al., 1998; Gahagan et al., 1988). In particular, fracture zones, active and extinct ridges and pseudofaults can produce strong gravity signals making them ideal mapping targets. A recent satellite altimetry-derived vertical gravity gradient (VGG) dataset (Sandwell et al., 2014) resolves structures as small as 6 km in width, enabling improved mapping of seafloor structures compared to previous versions. Increased resolution not only reveals new seafloor structures, but also confirms the existence of structures previously identified with lower confidence, which can then be used to improve plate kinematic models and constrain the timing of plate boundary reorganizations.

VGG mapping in Eocene seafloor in the eastern Indian Ocean has revealed a number of distinctive tectonic lineations that are datable using magnetic anomaly picks. Specifically we have identified possible extinct Indian-Antarctic ridge segments, conjugate pseudofaults and an oceanic microplate that underwent independent rotation (Figure 1a). The significance of these structures is two-fold. Not only is this one of the first times a Pacific-style microplate has been identified in the Indian Ocean, suggesting geophysical conditions at the Indian-Antarctic ridge probably resembled those that have dominated at Pacific ridges, however the formation of these structures also coincides with, and we argue is linked to the history of the India-Eurasia collision – the time of which is a major and long-standing controversy in plate tectonics. Microplate formation as a means of dating the India-Eurasia collision is completely independent to those timing constraints derived from continental geology or the India-Eurasia convergence history.

1.1 India-Eurasia collision and its seafloor record

One of the most intensively studied and strongly debated issues in plate tectonics is the timing and nature of the India-Eurasia collision. This event marked the closure of the NeoTethys Ocean basin, the youngest and final of the Tethyan oceans that separated Gondwana from Asia since the Paleozoic, and moreover it led to the rise of the Himalayas, the highest mountain chain on Earth. Proposed timings of the India-Eurasia collision vary by more than 30 Myr (e.g. Patriat and Achache, 1983; Searle et al., 1987; Klootwijk et al., 1992; Lee and Lawver, 1995; Rowley, 1998; Aitchison et al., 2007; van Hinsbergen et al., 2012; Zahirovic et al., 2012; Bouilhol et al., 2013; Gibbons et al., 2015), and there is debate over whether there was a single continent-continent collision event (e.g. Patriat and Achache, 1984; Lee and Lawver, 1995; Garzanti, 2008) or multiple collisions, with India first colliding with an island arc and later with Eurasia (e.g. Aitchison et al., 2007; Zahirovic et al., 2012; Bouilhol et al., 2013), or with a microcontinent-Eurasia collision followed by the India-Eurasia collision (van Hinsbergen et al., 2012).

Different observations have been used to constrain the timing and nature of the event, including changes in sedimentation patterns – such as the cessation of marine sedimentation in the suture zone and the beginning of continental molasse sedimentation (e.g. Searle et al., 1987; Aitchison et al., 2007), arc magmatic records – for instance the ending of calc-alkaline magmatism (e.g. Bouilhol et al., 2013), the decrease in India-Asia convergence inferred from magnetic lineations in the Indian Ocean (Molnar and Taponnier, 1975; Patriat and Achache, 1984; Lee and Lawver, 1995), basin subsidence patterns (Rowley, 1998), paleomagnetic data from the Indian plate and Himalayan region (Klootwijk et al., 1992), and the analysis of the mantle structure beneath the Tethyan region as inferred from seismic tomography models (van der Voo et al., 1999; Replumaz et al., 2004; Hafkenscheid et al., 2006). Additionally, global mantle convection modeling combined with seismic tomography analysis has enabled the testing of existing end-member kinematic models (Zahirovic et al., 2012). There is growing support for a complex multiple collision model in which India collided with an island-arc that was outboard of Asia at ~55-50 Ma, the Kohistan-Ladakh Arc, and then final India-Eurasia collision occurred closer to 40 or 30 Ma (e.g. Hafkenscheid et al.,

79 2006; Aitchison et al., 2007; Zahirovic et al., 2012; Bouilhol et al., 2013; Gibbons et al., 2015) and was likely
80 diachronous (e.g. Zahirovic et al., 2012). Furthermore the collision of India with Eurasia may be more
81 accurately defined as a protracted event that included a ‘soft’ collision phase followed by a ‘hard’ collision
82 phase (e.g. Gibbons et al., 2015).

83

84 Recently, Cande and Patriat (2015) suggested that the slowdown of India around chron 21o (47.3 Ma),
85 which is sharper using the GTS12 timescale (Ogg, 2012) than in previous timescales, is consistent with the
86 initial India-Eurasia collision. However, they noted some ambiguity in this timing considering that the sharp
87 change in azimuth of seafloor spreading between the Capricorn and African plates does not occur until
88 after chron 20o (43.4 Ma). This ambiguity is also reflected in a recent review of the India-Eurasia collision
89 using a synthesis of a range of marine geophysical and continental geological observations by Gibbons et al.
90 (2015), who proposed that India collided with an intraoceanic arc at ~52 Ma (arc-continent collision),
91 followed by an initial soft collision of India with Eurasia (continent-continent collision) around 44 ± 2 Ma.

92 **2 Oceanic microplates**

93

94 During spreading ridge reorganizations sections of oceanic crust can be transferred from one plate to
95 another due to instantaneous ridge jumps (e.g. Small, 1995) or ridge propagation into existing seafloor
96 (Hey, 1977), resulting in asymmetric lithosphere accretion. In the latter case, the captured rigid blocks are
97 commonly referred to as microplates (also ‘paleoplates’). Microplates are rigid bodies between two active
98 spreading ridges that rotate approximately independently of neighbouring plates (Mammerickx and
99 Klitgord, 1982). Spreading dwindles and then ceases at one of the ridges, leading to detachment of the
100 microplate from the spreading axis and transfer to one of the major plates. The paleoplate consists of both
101 the captured lithosphere, and the lithosphere that accreted during dual spreading (Mammerickx and
102 Klitgord, 1982). Tebbens et al. (1997) expanded the definition of Mammerickx and Klitgord (1982) to
103 include microplate formation in the absence of ridge death. This was based on their discovery of the Friday
104 Microplate in the southeastern Pacific, ~500 km west of the Chile Ridge (Figure 2). According to Tebbens et

105 al. (1997) the Friday Microplate formed from the step-wise migration of the Pacific-Nazca-Antarctic triple
106 junction at chron 5A (~12 Ma). The Chile Ridge (Nazca-Antarctic spreading arm of the triple junction)
107 propagated into the Nazca plate, whereby isolating a section of Nazca crust. Asymmetry in the shape of the
108 associated Friday and Crusoe pseudofaults confirms there was independent rotation of the Friday
109 Microplate during formation (Tebbens et al., 1997).

110

111 Microplate formation and ridge propagation have been intensively studied in the Pacific for more than 40
112 years (e.g. Hey, 1977; Hey et al., 1980; Hey and Wilson, 1982; Hey et al., 1988; Mammerickx et al., 1988;
113 Schouten et al., 1993; Searle et al., 1993; Bird and Naar, 1994; Tebbens et al., 1997; Tebbens and Cande,
114 1997; Blais et al., 2002; Eakins, 2002; Eakins and Lonsdale, 2003). Here there are several actively forming
115 microplates (e.g. Easter, Juan Fernandez, Galapagos) and detached Cenozoic ones (e.g. Mathematician,
116 Bauer, Friday, Selkirk, Hudson) (Figure 2).

117

118 Building on the work of Schouten et al. (1993), both Bird and Naar (1994) and Eakins (2002) emphasised
119 that plate reorganizations are a trigger for changing the coupling at free-slip boundaries, that can result in
120 tearing of one or both plates and the initiation of a propagator from a ridge spreading offset (see summary
121 of Hey, 2004). As the propagator grows the microplate core rotates due to the drag of the adjacent plates.
122 Both transpression or transtension-inducing plate motion changes can increase shear coupling across a
123 previously free-slipping boundary (Bird and Naar, 1994; Eakins, 2002).

124

125 In addition to plate motion changes, hotspot activity and fast seafloor spreading can drive or facilitate ridge
126 propagation and microplate formation, as they contribute to stress changes at the ridge and production of
127 regions of hot, thin or weakened lithosphere that is able to concentrate stress (e.g. Hey et al., 1985; Bird
128 and Naar, 1994; Hey, 2004). Furthermore, hotspot activity also produces elevated topography, which is a
129 driver of ridge propagation, with ridge propagation directed away from hotspots (Phipps Morgan and
130 Parmentier, 1985). Microplate formation can also occur during step-wise triple junction migration (Tebbens
131 et al., 1997; Tebbens and Cande, 1997; Bird et al., 1999).

132

133 Microplate rotation produces ‘oblique seafloor’ rather than typical ridge parallel and perpendicular
134 structures (Hey, 2004). A fan shaped pattern of isochrons and rotated abyssal hills are characteristic
135 features (Hey et al., 1988; Mammerickx et al., 1988; Eakins, 2002; Hey et al., 2004). Ridge propagation
136 produces a pair of pseudofaults across which young lithosphere formed at the new ridge is juxtaposed
137 against older lithosphere. These lineations, defining seafloor age contrasts, are commonly identifiable as
138 negative gravity anomalies. Pseudofault pairs are often near mirror images of each other, although
139 microplate rotation can reduce this symmetry (Tebbens et al., 1982). If spreading ceases at one of the
140 microplate boundaries, signalling an end to dual spreading, then an extinct ridge may also be identifiable in
141 the seafloor fabric, as is adjacent to the Mathematician, Hudson, Selkirk and Bauer microplates.

142 **3 Methodology**

143

144 The VGG dataset of Sandwell et al. (2014) is used to map seafloor fabric in the eastern and southern Indian
145 Ocean, specifically structures that formed at the Southeast Indian Ridge from spreading between India and
146 Antarctica. Compared to free-air gravity, VGG data better resolve short wavelength structures such as
147 fracture zones. By combining new altimeter measurements from the CryoSat-2 and Jason-1 satellites with
148 older data from Geosat and ERS-1 the Sandwell et al. (2014) VGG dataset provides unprecedented
149 resolution and resolves structures as small as 6 km in width. It therefore provides a unique opportunity to
150 improve seafloor mapping and confirm or identify new tectonic structures that can constrain plate tectonic
151 models. Multi-beam ship track data collected during the Sojourn Expedition Leg 4, R/V Melville, 1997, were
152 also used during mapping (Figure 1) (NOAA National Centers for Environmental Information, 2004).

153

154 Structures identified in the VGG maps are dated using magnetic anomaly picks where possible. The primary
155 source of magnetic anomaly picks in our regions of interest is Cande et al. (2010). Several magnetic
156 anomaly picks from Ségoufin et al. (2004) are also used to supplement those from Cande et al. (2010). The
157 GTS2012 timescale of Ogg (2012) is adopted, and a ‘y’ or ‘o’ is used to describe whether the young or old

158 end of the magnetic chron was picked, respectively. Absolute seafloor ages are supplemented with seafloor
159 ages derived from relative dating. Relative age dating helps clarify the sequence of tectonic events in the
160 absence of tight absolute age constraints, and can provide valuable estimates on the minimum and
161 maximum ages of structures. Cande and Patriat (2015) provide finite Euler rotation poles for spreading
162 between India and Antarctica and we have used these data, in conjunction with the open-source plate
163 reconstruction software *GPlates*, to calculate spreading rates at the Southeast Indian Ridge, specifically at
164 the point shown in Figure 1. These spreading rates allow us to estimate seafloor ages where magnetic
165 anomaly picks are absent.

166 **4 Eocene seafloor tectonic fabric of the eastern and southern Indian**

167 **Ocean**

168
169 In the eastern Indian Ocean a >500 km long E-W to NW-SE trending structure that resembles an extinct
170 spreading ridge is located at ~21.5°S, to the west of the Ninetyeast Ridge (Figures 1 and 3). It has a step-like
171 pattern that mainly comprises segments 30-70 km in length with a negative VGG signature, although some
172 segments comprise a positive VGG signature. The structure curves southwards in the east, along the
173 western edge of the Ninetyeast Ridge.

174
175 To the south of the eastern part of the extinct ridge-like structure abyssal hill fabric is discernable in VGG
176 maps (Figures 1 and 3). Near the chron 20o (43.4 Ma) magnetic anomaly picks of Cande et al. (2010) the
177 abyssal hill lineations are oriented ~97° (Figure 1c). As abyssal hills form roughly perpendicular to the
178 direction of seafloor spreading, their orientation indicates that the direction of spreading was
179 approximately N-S and that this seafloor formed prior to the major clockwise change in spreading direction
180 at the ridge that occurred at chron 20 according to Cande et al. (2010). The abyssal hills north of this
181 appear to have been rotated counterclockwise by 25°. Their orientation is not perpendicular to the
182 direction of spreading that preceded (~N-S), nor post-dated (~SSW-NNE), the chron 20 spreading

183 reorganization at the Southeast Indian Ridge, suggesting that the crust was rotated after formation (Figure
184 3).

185

186 Lying 100-200 km to the south of the extinct ridge-like feature is a NW-SE trending linear structure, ~350
187 km in length and characterized by a VGG low (Figures 1 and 3). A comparable structure (trending NNW-SSE)
188 is also observed on the Antarctic Plate in the same spreading corridor, north-northwest of the Kerguelen
189 Plateau (Figures 1 and 3). Their VGG widths (~10 km) are similar to, or slightly smaller than adjacent
190 fracture zones. These structures, however, are oblique to adjacent fracture zones and nearly orthogonal to
191 fracture zones formed in younger crust, and therefore are not fracture zones despite having a similar
192 gravity signature. At their eastern ends they emanate from the same location as fracture zones E1-2 (Figure
193 3) that continue in younger crust and can be traced to the present-day spreading ridge. These structures
194 are also a divide between a highly segmented spreading system with closely spaced fractures zones
195 (younger crust), and a spreading system with widely spaced fracture zones and 'W' shaped lineations
196 produced by the migration of non-transform ridge offsets (older crust).

197

198 On the Indian Plate, to the north of the proposed extinct ridge, there is a zone of chaotic seafloor fabric
199 devoid of fracture zone traces (Figure 1a), unlike what has previously been identified from free-air gravity
200 (Krishna et al., 2012). Here distinctive 'W' shaped lineations (oblique to the direction of spreading) record
201 the migration of small ridge offsets, that is, back and forth ridge propagation similar to what is described by
202 Phipps-Morgan and Sandwell (1994) along the Southeast Indian Ridge (Figure 1c). The formation of these
203 features reveals the absence of a stable transform fault at the spreading ridge that is required for the
204 formation of fracture zones. This type of seafloor fabric is also seen on the Antarctic Plate (Figure 1b)
205 between fracture zones B and C, and C and E (Figure 3). Additionally, on the Indian Plate in this region of
206 chaotic seafloor fabric the seafloor appears undulate, in contrast to the relatively flat seafloor seen to the
207 west of fracture zone C away from this zone (Figure 4), likely related to Kerguelen Plume activity.

208

209 A comparison of seafloor fabric on the Indian and Antarctic plates reveals regions of symmetry and
210 asymmetry, with seafloor fabric symmetry expected from a simple spreading history. To the east of the
211 fracture zone C on both plates (Figure 3) there is a distinctive asymmetry in the seafloor fabric (from at
212 least chron 29o, Figure 1b-c) that supports previous suggestions of ridge jumps and asymmetric crustal
213 accretion (e.g. Krishna et al., 1995). To the west of fracture zone C (in the spreading corridors between
214 fracture zones A-B and B-C, Figure 3) the seafloor fabric is largely symmetric, with features on one plate
215 mirrored on the other plate. For instance, a set of distinctive ‘W’ shaped lineations on the Indian plate
216 (seafloor older than chron 22o), which are oblique to the fracture zones, are also seen on the Antarctic
217 plate, although here their signal is slightly weaker. These pseudofault and extinct ridge traces are produced
218 during short-lived ridge propagation events that have been widely observed at the Southeast Indian Ridge
219 (Phipps Morgan and Sandwell, 1994).

220 4.1 Tectonic fabric interpretations

221

222 The tectonic fabric features described above are most likely a result of ridge extinction, microplate
223 formation and rotation, and a ridge jump involving ridge propagation. In particular they share a strong
224 resemblance to well-studied structures produced by microplate formation, ridge extinction and ridge
225 propagation in the eastern Pacific.

226

227 The pattern seen in the VGG maps created by the proposed extinct ridge, particularly its segmentation, is
228 very similar to that of currently active mid-ocean ridges. Considering that this structure also largely trends
229 perpendicular to the direction of spreading between the Indian and Antarctic plates during the Eocene, in a
230 region of previously identified ridge jumps, we interpret this feature as an extinct spreading ridge. The scale
231 of segmentation observed is similar to that of the present-day central Mid-Atlantic and Central Indian
232 ridges, and is consistent with a slow-intermediate spreading regime with half-spreading rates less than 30
233 mm/yr (Sandwell and Smith, 2009). This is much slower than the spreading rate during creation of older
234 crust in the region, to the north of the extinct ridge, which exceeded 50-60 mm/yr (half-rate) during the
235 latest Cretaceous and Paleocene (Seton et al., 2012; Cande and Patriat, 2015). An increase in roughness

236 adjacent to the ridge, compared to older seafloor, and increased ridge segmentation likely reflect a
237 decrease in spreading rate, which can occur during the demise of a ridge prior to extinction (Livermore et
238 al., 2000).

239

240 The curvature of this structure in the east adds further support to its classification as an extinct ridge.
241 Curvature and migration of a dying spreading ridge have been observed in the Pacific associated with
242 formation of the Bauer and Selkirk microplates (Eakins and Lonsdale, 2003; Blais et al., 2002). In these
243 scenarios migration of the dying ridges occurred during dual-spreading and in both instances migration was
244 towards the new ridge and microplate core. At the Bauer Microplate the Galapagos Rise grew in a
245 southwestward direction during clockwise rotation, and in response the seafloor rotated in a
246 counterclockwise direction to the north of the Atahualpa Scarp and west of the propagating ridge.
247 Specifically there was a $\sim 25^\circ$ counterclockwise rotation of pre-existing seafloor which is observed in abyssal
248 hill trends identified from multibeam bathymetry data (Eakins and Lonsdale, 2003, e.g. Figure 3, p174).
249 Similarly to the Bauer Microplate, a 25° counterclockwise rotation of abyssal hill fabric is also identified to
250 the south of the eastern Indian Ocean proposed extinct ridge, adjacent to where the ridge curves
251 southward (Figures 1 and 3). This suggests that southward growth of the ridge prior to extinction disrupted
252 pre-existing seafloor fabric.

253

254 Rotation of the dying ridge is also demonstrated by the curvature of what is interpreted to be a fracture
255 zone that formed at the ridge (Figure 3, fracture zone D). The northern fracture zone strand curves to the
256 east, while the southern fracture zone strand curves to the west. The asymmetry seen between the
257 northern and southern strands is consistent with a rotating ridge, as if there was migration of a transform
258 offset during spreading, which also produces structures oblique to the direction of spreading, then the
259 resultant seafloor traces would be symmetric across the ridge. Near this fracture zone abyssal hill fabric is
260 identified from ship track multibeam bathymetry (Sojourn Expedition Leg 4, R/V Melville, 1997) (Figure 5).
261 The abyssal hills have an azimuth of $\sim 110\text{-}120^\circ$ to the east of fracture zone D, while directly to the east and

262 west of fracture zone C they have an azimuth of $\sim 90-95^\circ$, which is perpendicular to the direction of
263 spreading between the Indian and Antarctic plates.

264

265 The very distinctive linear, 350 km long NW-SE and NNW-SSE trending gravity lows on the Indian and
266 Antarctic plates, respectively, are interpreted to be conjugate features. We interpret these as pseudofaults
267 of a new, westward propagating ridge that succeeded the extinct ridge. The pseudofaults are slightly
268 asymmetric indicating independent motion of the microplate plate and their low angle with respect to the
269 pre-existing and newly established ridge indicates fast propagation. The pseudofaults are to the south of
270 the extinct ridge indicating that the plate boundary reorganization involved a southward ridge jump.

271 Pseudofault pairs are common and distinctive seafloor structures across which there is an age contrast (yet
272 no relative motion, hence 'pseudo'), such as the Pacific Friday and Crusoe troughs (Chile Ridge, e.g.
273 Tebbens et al., 1997, Figure 1), the Henry and Hudson troughs (Pacific-Antarctic ridge, e.g. Tebbens and
274 Cande, 1982, Figures 1 and 3) and the Moctezuma and Michoaca troughs (near the Mathematician
275 Microplate, e.g. Mammerickx et al., 1988, Figure 2). These eastern and southern Indian Ocean pseudofaults
276 produce a similarly distinctive gravity signal.

277

278 The ridge propagation event was accompanied by the establishment of well-defined transform faults at the
279 origin of propagation, and this is seen in the fracture zone patterns. Fracture zones 'E1-2' (Figure 3) initiate
280 at the time of propagation and are absent in older crust. Fracture zones form from stable transform fault
281 ridge offsets that are typically greater than 30 km (MacDonald et al., 1991), and therefore the
282 establishment of fracture zones 'E1-2' suggests that the offset at the mid-ocean ridge from which the
283 propagating ridge spawned was small and subsequently grew.

284

285 4.2 Temporal constraints

286 Magnetic anomaly picks help constrain seafloor ages in these regions of the Indian Ocean where we have
287 identified a pseudofault pair and extinct ridge (Cande et al., 2010; Ségoufin et al., 2004). They are more
288 densely distributed in the spreading corridor to the west of fracture zone C, compared to the spreading

289 corridors to the east (Figure 3). However, some key picks near the extinct ridge and pseudofaults provide
290 crucial information on timings of events. Combining these data with relative dating, and age estimates
291 derived from spreading rate assumptions, helps build a sequence of events with approximate ages for ridge
292 extinction, propagation and microplate formation.

293

294 Although sparse, magnetic anomaly picks near the extinct ridge can help approximate the timing of
295 extinction. Cande et al.'s (2010) closest magnetic anomaly pick to the extinct ridge, and in fact one of only
296 two from their study that is located in this spreading corridor within 1000 km from the ridge, is a single
297 chron 22o (49.3 Ma) pick located ~150 km (spherical distance) from the western end of the ridge (Figures
298 1c and 3). Based on the spreading rates of Cande and Patriat (2015), calculated for this part of the
299 Southeast Indian Ridge (Figure 1a – orange star), extinction likely occurred after chron 20o (43.4 Ma) in
300 order for 150 km of crust to be produced. Their spreading rates predict that just under 150 km of crust was
301 produced between chrons 22o and 20o. Two chron 21o (47.3 Ma) picks of Ségoufin et al. (2004) are located
302 ~30 km north of the extinct ridge (Figure 3). Based on Cande and Patriat's (2015) spreading rates, this
303 would place the timing of extinction at chron 21y (45.7 Ma) at a minimum. It is difficult to place tight age
304 constraints on extinction as it is uncertain whether spreading slowed at the dying ridge segment during its
305 demise.

306

307 Similarly to the extinct ridge, the timing of ridge propagation and formation of the pseudofaults can be
308 estimated using magnetic anomaly picks and spreading rate assumptions. When combined, these
309 observations are found to be consistent with each other.

310

311 The age of the seafloor to the east of the pseudofaults, in the spreading corridor east of fracture zone E2
312 (Figure 3), differs between the Antarctic and Indian plates. On the Antarctic plate the seafloor formed at
313 the time of chron 20o (43.4 Ma), whereas on the Indian plate the chron 20o picks are located 230 km
314 south, and therefore the seafloor is older. An age contrast strongly suggests that ridge propagation
315 initiated from the site of a ridge offset rather than at a ridge tip, as in the instance of propagation from a

ridge tip, this age contrast should be the same on both plates. A model for an intratransform origin for ridge propagation was described in detail by Bird and Naar (1994) and has been proposed for many microplates in the Pacific, including the Bauer, Henry, Friday and Selkirk microplates (Eakins and Lonsdale, 2003; Cande et al., 1982; Tebbens et al., 1997; Tebbens and Cande, 1997; Blais et al., 2002). This is also seen to the west of Australia where ridge propagation from the large offset Wallaby-Zenith fracture zone appears to have initiated and then failed after ~100 km leaving two pseudofault traces. The nature of the age contrast across these spreading corridors is consistent with formation at a right-offset transform, which continued to present-day (Seton et al., 2012). Ridge propagation from a right offset transform indicates that propagation initiated at a time older than chron 20o, and younger than the time of formation of the crust to the east of the pseudofault on the Indian plate. Considering that ~200 km of Indian plate crust was produced between chrons 20o and chron 23.2o (47.3-51.8 Ma) (Cande and Patriat, 2015) this suggests ridge propagation and pseudofault formation initiated after chron 23.2o (51.8 Ma).

328

In support of ridge propagation after chron 23.2o (51.8 Ma) is the observation that the pseudofault on the Antarctic Plate cuts seafloor that is chron 22o in age (49.3 Ma) (Figure 3). Magnetic anomaly picks from both Cande et al. (2010) and Ségoufin et al. (2004) date seafloor in this region, which strengthens the observation. Propagation must therefore have occurred after this time.

333

Two chron 21o magnetic anomaly picks of Ségoufin et al. (2004) are located along strike and adjacent to the pseudofault (within 10 km) and may date the youngest seafloor formed at the new spreading centre. These ages are consistent with age estimates derived using the spreading rates of Cande et al. (2015). At the western end of the pseudofaults ~170 km of crust was produced on each flank of the new spreading ridge by the time of chron 18.2o (40.1 Ma), based on the isochron that we constructed using the magnetic anomaly picks of Cande et al. (2010) (trace of the Antarctic-Indian mid-ocean ridge in Figure 3). At the eastern end of the pseudofaults closer to ~200 km of crust was produced on each flank. Based on spreading rate calculations for this portion of the ridge, propagation initiated around chron 21o (47.3 Ma) and was completed before the end of chron 21 (45.7 Ma), and therefore was likely completed in less than 2 Myr at a

343 rate of c. 200 mm/yr. Considering that the full spreading rate at the Antarctic-Indian ridge between c23.2o
344 and c20o ranged from ~110 to 75 mm/yr, this propagation rate is consistent with observations from
345 intermediate-fast spreading ridges that ridge propagation can occur at rates of 50-150% of the full
346 spreading rate at the ridge (Phipps Morgan and Sandwell, 1994).

347

348 In summary, a variety of age observations support rapid ridge propagation during chron 21. Ridge
349 extinction is more difficult to constrain, but must have occurred after chron 21. The demise of spreading at
350 the ridge may even have continued until after chron 20. Estimating the ages of these events is made
351 difficult by the possibility of a period of slow spreading immediately prior to ridge death and immediately
352 following the initiation of spreading at the new ridge.

353 **5 Microplate formation in the eastern Indian Ocean**

354

355 Seafloor tectonic fabric features, that are well-defined in recent VGG data (Sandwell et al., 2014), record a
356 mid Eocene reorganization at the Southeast Indian Ridge to the west of the Ninetyeast Ridge, involving a
357 southward ridge jump and formation of an oceanic microplate. We refer to this microplate as the
358 Mammerickx Microplate, after Dr Jacqueline Mammerickx, a pioneer in seafloor mapping, in particular the
359 mapping of microplates in the Pacific. Formation of the Mammerickx Microplate involved dual-spreading,
360 including rotation of the dying ridge axis, and the formation of seafloor fabric features that are observed in
361 the Pacific Ocean at the sites of well-studied microplates. The sequence of events associated with the
362 reorganization is depicted in Figure 6 and is constrained by magnetic anomalies (Cande et al., 2010;
363 Ségoufin et al., 2004), relative age dating, and seafloor age estimates from the seafloor spreading data of
364 Cande and Patriat (2015).

365

366 Westward ridge propagation from a developing right-offset transform fault initiated at approximately
367 chron 21o (47.3 Ma) resulting in a southward ridge relocation. Propagation was rapid, c. 200 mm/yr, and
368 was likely completed by the end of chron 21 (45.7 Ma). Spreading at the dying ridge likely ceased some

time during or after chron 20 (43.4-42.3 Ma). During its demise the ridge grew southward and rotated clockwise, which in turn caused a counterclockwise rotation of existing seafloor fabric, such as abyssal hills to the south. This reorganization was not only associated with a ridge jump, but also the establishment of a right-offset transform fault to the west of the Ninetyeast Ridge that has persisted to present-day. Ridge propagation coincides with the rapid change in spreading azimuth at the Central and Southeast Indian ridges identified by Cande et al. (2010).

6 Discussion

Identification of a microplate in the Indian Ocean is spatially significant as until now microplate formation has almost entirely been restricted to the Pacific, specifically at the East Pacific Rise and Pacific-Antarctic Ridge. This suggests that at the time of Mammerickx Microplate formation, kinematic or geodynamic conditions at this part of the Indian-Antarctic ridge shared similarities with those that have frequently been present at eastern Pacific ridge systems, yet largely absent in the Atlantic and elsewhere in the Indian Ocean.

As summarised by Hey (2004) the stresses related to plate reorganizations, fast spreading and hotspot activity can trigger or promote ridge propagation and the formation of microplates. Additionally, episodic triple junction migration has been associated with ridge propagation and microplate formation in the eastern Pacific (Bird et al., 1999; Tebbens et al., 1997; Tebbens and Cande, 1997); specifically formation of the Hudson, Friday and Juan Fernandez microplates occurred during migration of the Pacific-Antarctic-Nazca/Farallon triple junction (Tebbens and Cande, 1982; Tebbens et al., 1997; Tebbens and Cande, 1997; Eakins, 2002). Each of these four drivers may have played a role in formation of the Mammerickx Microplate.

Ridge propagation at chron 21o time (47.3 Ma) coincides with proposed timings of India-Eurasia collision; a major plate boundary shake-up. Additionally, half-spreading rates at the Indian-Antarctic ridge exceeded 50

395 mm/yr prior to ridge propagation (Cande and Patriat, 2015), this is similar to present-day spreading rates at
396 the fast spreading East Pacific Rise of 50 to >70 mm/yr (DeMets et al., 2010) and Cenozoic rates that
397 typically exceeded 70 mm/yr (Müller et al., 2008). Furthermore, it has been proposed that hotspots can
398 influence ridge behaviour over distances of up to 1400 km (Ribe and Delattre, 1998), and based on three
399 different absolute reference frames (O'Neill et al., 2005; Doubrovine et al., 2012) the microplate formed
400 less than 1100 km from the Kerguelen Hotspot centre point (location from Whittaker et al., 2015), or less
401 than 700 km from the hotspot assuming a 400 km plume radius (Montelli et al., 2004) (Table 1). Ridge
402 propagation, to the west, was directed away from the hotspot as predicted by models of ridge propagation
403 (Phipps Morgan and Parmentier, 1985) and as seen in the Pacific (Hey and Wilson, 1982). Finally, plate
404 reconstructions for the eastern Indian Ocean at this time (e.g. Whittaker et al., 2013) model a triple
405 junction east of the microplate, with the Southeast Indian Ridge (comprising the Indian-Antarctic and
406 Australian-Antarctic ridges) connected to the Wharton Ridge (Indian-Australian ridge) via a transform along
407 the Ninetyeast Ridge (e.g. Seton et al., 2012).

408

409 We consider that a plate reorganization in the Indian Ocean, that included a rapid slow down in spreading
410 between India and Antarctica at chron 21o (Cande and Patriat, 2015), triggered microplate formation. Plate
411 reorganizations can change the stress field of a plate and the coupling across free-slip boundaries, leading
412 to tearing and rift propagation (Bird and Naar, 1994; Eakins, 2002). In the eastern Indian Ocean, the chron
413 21o reorganization altered the configuration of the Antarctic-Indian spreading ridge. Tearing from a newly
414 established transform lead to westward ridge propagation and ultimately formation of the Mammerickx
415 Microplate. This shares similarities with the formation of the Hudson Microplate, which involved ridge
416 propagation from the newly formed Raitt transform (Eakins, 2002).

417

418 We further suggest that high spreading rates and proximity to the Kerguelen Plume likely facilitated the
419 microplate formation event that was triggered by the chron 21o reorganization. Fast spreading rates and
420 hot asthenosphere from plume activity can lead to formation of weak and thin lithosphere that is less able
421 to resist cracking and rift propagation (Hey et al., 1985; Naar and Hey, 1989; Bott et al., 1993), and

422 therefore produce a tectonic scenario conducive to microplate formation. These conditions, however, were
423 both present for tens of millions of years in this part of the Indian Ocean and therefore are not considered
424 as 'triggers' for the event. Fast spreading rates, exceeding 50 mm/yr (half-rate), were present at the Indian-
425 Antarctic ridge for >20 Myr prior to a rapid decrease at chron 21o time (47.3 Ma) (Cande and Patriat, 2015).
426 A rapid increase in spreading rate at the Southeast Indian Ridge occurred at chron 31y (68 Ma), with a peak
427 half-spreading rate of 90 mm/yr recorded between chrons 29o and 28y (66-63 Ma) (Cande and Patriat,
428 2015). There has been a hotspot influence at the ridge for even longer. Whittaker et al. (2013) showed that
429 over at least a 65 Myr period from 108 to 43 Ma, the position of the Australian-Indian-Antarctic triple
430 junction was influenced by the Kerguelen Plume; the ridge system remained close to the plume, within 500
431 km during the period, and as close as 100 km by 43 Ma, assuming hotspot fixity. The southerly jump of the
432 Indian-Antarctic ridge, achieved through microplate formation, is consistent with the ridge system moving
433 towards and remaining close to the hotspot.

434
435 Fast spreading and plume activity may also be responsible for a large region of distinctively undulate and
436 chaotic seafloor north of the extinct ridge (Figure 4). Fast spreading prior to microplate formation
437 hampered the establishment of stable transform offsets at the Indian-Antarctic ridge, resulting in the back
438 and forth migration of ridge offsets. According to Naar and Hey (1989) half-spreading rates exceeding 75
439 mm/yr prevent transform fault formation, however here spreading rates were slightly slower at times,
440 exceeding 50 mm/yr. Therefore plume activity, which can influence ridge behaviour over distances of up to
441 1400 km (e.g. Ribe and Delattre, 1998), likely contributed to the formation of weaker lithosphere, which
442 when coupled with fast spreading rates resulted in back and forth ridge propagation. We speculate that
443 pulses of plume activity may be responsible for the undulating seafloor topography and seamount like
444 structures in this region.

445
446 It is difficult to access whether triple junction migration played a role in Mammerickx Microplate formation,
447 as the plate boundary between Australia and Antarctica, in the region of the Kerguelen Plateau and Broken
448 Ridge, may not have been a discrete boundary prior to 43 Ma, rather it may have been a diffuse boundary,

449 or composed of short-lived boundaries (Whittaker et al., 2013). The model for triple junction migration
450 proposed by Bird et al. (1999) and applied to microplate formation in the Pacific involved a system of three
451 discrete and well-established plate boundaries, and it is uncertain whether it can be applied in the eastern
452 Indian Ocean at this time. Additionally, ridge propagation leading to microplate formation did not occur
453 directly at the triple junction.

454

455 The timing of microplate formation in the eastern Indian Ocean at 47 Ma is temporally significant as this
456 time, corresponding to chron 21o, had been proposed as the initial India-Eurasia collision time by a number
457 of authors (see summary in Cande and Patriat, 2015). Although there is considerable spread in the
458 published timings of the India-Eurasia collision, and debate over the number and nature of collision events,
459 formation of the Mammerickx Microplate adds support for a collision at ~47 Ma, as the initial continental
460 collision between India and Eurasia would be expected to lead to a significant change in the stress regime
461 at the Indian-Antarctic ridge. This initial stage of continent-continent collision, likely the ‘soft’ collision
462 stage (Gibbons et al., 2015), not only slowed spreading at the Indian-Antarctic ridge (Cande and Patriat,
463 2015), but it also altered ridge segmentation and initiated ridge propagation. The connection between the
464 onset of mountain building in Tibet, the post-47 Ma slowdown of the Indian Plate and the subsequent
465 reorganization of plate boundaries in the Indian Ocean as proposed in Copley et al.’s (2010) analysis of
466 Indian Plate driving forces fits with our observation of microplate formation recording the onset of this set
467 of events in the Indian Ocean. There is a coincidence in timing between the India-Eurasia collision and a
468 number of plate boundary reorganization events in other ocean basins (Whittaker et al., 2007), as well as
469 the formation of the bend in the Hawaiian-Emperor seamount chain. However, it is beyond the scope of
470 this investigation to test geodynamic linkages between these widely distributed events.

471 **7 Conclusions**

472 Our analysis of a new satellite-derived global VGG dataset (Sandwell et al., 2014), with unprecedented
473 resolution, has revealed an extinct Pacific-style microplate in the eastern Indian Ocean — the ‘Mammerickx
474 Microplate’. The Mammerickx Microplate is located west of the Ninetyeast Ridge (centred on ~21.5°S),

475 formed at the Indian-Antarctic ridge during the Eocene and was captured by the Indian Plate. To our
476 knowledge this is the first of its kind in the Indian Ocean. A variety of seafloor structures, identified from
477 high-resolution satellite-derived VGG data, match those at well-studied microplates in the eastern Pacific
478 (e.g. Bauer, Friday, Mathematician, Hudson, Selkirk). These structures include conjugate pseudofaults
479 produced by propagation of the new ridge, an extinct ridge and rotated abyssal hill fabric, the latter of
480 which is observed in the VGG and ship track multibeam bathymetry data (Sojourn Expedition Leg 4, R/V
481 Melville, 1997). The observation that the microplate underwent counterclockwise rotation reflects that
482 dual spreading occurred prior to ridge extinction at the northern pre-existing ridge. This indicates there was
483 a brief period during which the motion of the microplate was independent to that of the neighbouring
484 Indian and Antarctic plates, likely due to drag from the adjacent plates (Schouten et al., 1993; Eakins, 2002).

485
486 We propose that the formation of the Mammerickx Microplate is linked with the initiation of the India-
487 Eurasia collision, with ridge propagation triggered by the event. Magnetic anomaly picks, relative age
488 dating, and age estimates using recently published spreading rates for the Indian-Antarctic ridge (Cande
489 and Patriat, 2015), were used to constrain microplate formation to chron 21o (47.3 Ma), with the initiation
490 of westward directed propagators at this time.

491
492 Plate motion changes during reorganization events, such as those related to tectonic collisions, have been
493 linked with microplate formation in the Pacific (e.g. Tebbens et al., 1997; Tebbens and Cande, 1997). In the
494 case of the Mammerickx Microplate, we suggest that westward ridge propagation from a newly formed
495 transform was triggered by the initiation of the India-Eurasia collision and resultant changes to the stress
496 regime at the ridge. This microplate formation event was coincident with a well-defined slow down in
497 seafloor spreading (Cande and Patriat, 2015). We further suggest that hotspot activity and fast spreading
498 rates (preceding collision), that are associated with warm, thin and weak lithosphere, facilitated ridge
499 propagation and microplate formation, yet were less likely to have acted as triggers as both were present
500 for tens of millions of years leading up to formation. They are also responsible for the production of chaotic
501 and undulate seafloor north of the microplate and west of the Ninetyeast Ridge, in which 'W' shaped

502 propagating ridge traces are common. Our dating of part of the history of the India-Eurasia collision is
503 novel, completely independent from previous conclusions drawn from continental geology and
504 convergence rate calculations, and represents the most precise and unambiguous date for the onset of
505 India-Eurasia collision.

506

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512 Version 23 of the global grids of gravity anomaly and VGG can be downloaded from the following ftp site
513 ftp://topex.ucsd.edu/pub/global_grav_1min. All figures were produced using the *Generic Mapping Tools*
514 (*GMT*) software (Wessel et al., 2013). The open-source plate reconstruction software *GPlates* (Boyden et
515 al., 2011) was used to compute the distance from the Kerguelen Plume to the initiation point of ridge
516 propagation using different absolute reference frames, and to produce the VGG raster reconstruction in
517 Figure 3. Magnetic anomaly picks were accessed from the compilation of Seton et al. (2014) from The
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521

522 References

523 Aitchison, J.C., Ali, J.R., Davis, A.M., 2007. When and where did India and Asia collide? *Journal of*
524 *Geophysical Research* 112, 1-19.
525 Becker, J.J., Sandwell, D.T., Smith, W.H.F., Braud, J., Binder, B., Depner, J., Fabre, D., Factor, J., Ingalls,
526 S., Kim, S.H., Ladner, R., Marks, K., Nelson, S., Pharaoh, A., Trimmer, R., Von Rosenberg, J., Wallace, G.,
527 Weatherall, P., 2009. Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution:
528 SRTM30_PLUS. *Marine Geodesy* 32, 355-371.

529 Bird, R.T., Naar, D.F., 1994. Intratransform origins of mid-ocean ridge microplates. *Geology* 22, 987-990.

530 Bird, R.T., Tebbens, S.F., Kleinrock, M.C., Naar, D.F., 1999. Episodic triple-junction migration by rift
531 propagation and microplates. *Geology* 27, 911-914.

532 Blais, A., Gente, P., Maia, M., Naar, D.F., 2002. A history of the Selkirk paleomicroplate. *Tectonophysics*
533 359, 157-169.

534 Bouilhol, P., Jagoutz, O., Hanchar, J.M., Dudas, F.O., 2013. Dating the India–Eurasia collision through arc
535 magmatic records. *Earth and Planetary Science Letters* 366, 163-175.

536 Boyden, J.A., Müller, R.D., Gurnis, M., Torsvik, T.H., Clark, J.A., Turner, M., Ivey-Law, H., Watson, R.J.,
537 Cannon, J.S., 2011. Next-generation plate-tectonic reconstructions using GPlates, in: G.R., K., Baru, C.
538 (Eds.), *Geoinformatics: Cyberinfrastructure for the Solid Earth Sciences*. Cambridge University Press,
539 Cambridge, pp. 95-114.

540 Cande, S.C., Patriat, P., 2015. The anticorrelated velocities of Africa and India in the Late Cretaceous
541 and early Cenozoic. *Geophysical Journal International* 200, 227-243.

542 Cande, S.C., Patriat, P., Dymment, J., 2010. Motion between the Indian, Antarctic and African plates in the
543 early Cenozoic. *Geophysical Journal International* 183, 127-149.

544 Copley, A., Avouac, J.P., Royer, J.Y., 2010. India-Asia collision and the Cenozoic slowdown of the Indian
545 plate: Implications for the forces driving plate motions. *Journal of Geophysical Research: Solid Earth*
546 (1978–2012) 115.

547 De Alteriis, G., Gilg Capar, L., Olivet, J.L., 1998. Matching satellite derived gravity signatures and
548 seismicity patterns along mid-ocean ridges. *Terra Nova* 10, 177-182.

549 DeMets, C., Gordon, R.G., Argus, D.F., 2010. Geologically current plate motions. *Geophysical Journal*
550 *International* 181, 1-80.

551 Doubrovine, P.V., Steinberger, B., Torsvik, T.H., 2012. Absolute plate motions in a reference frame
552 defined by moving hot spots in the Pacific, Atlantic, and Indian oceans. *Journal of Geophysical Research*
553 117.

554 Eakins, B.W., 2002. *Structure and Development of Oceanic Rifted Margins*, Earth Sciences. University of
555 California, San Diego.

556 Eakins, B.W., Lonsdale, P.F., 2003. Structural patterns and tectonic history of the Bauer microplate,
557 Eastern Tropical Pacific. *Marine Geophysical Researches* 24, 171-205.

558 Gahagan, L.M., Scotese, C.R., Royer, J.-Y., Sandwell, D.T., Winn, J.K., Tomlins, R.L., Ross, M.I., Newman,
559 J.S., Müller, R.D., Mayes, C.L., 1988. Tectonic fabric map of the ocean basins from satellite altimetry
560 data. *Tectonophysics* 155, 1-6, 11-26.

561 Gibbons, A.D., Zahirovic, S., Müller, R.D., Whittaker, J.M., Yatheesh, V., 2015. A tectonic model
562 reconciling evidence for the collisions between India, Eurasia and intra-oceanic arcs of the central-
563 eastern Tethys. *Gondwana Research* 28, 451-492.

564 Hafkenscheid, E., Wortel, M.J.R., Spakman, W., 2006. Subduction history of the Tethyan region derived
565 from seismic tomography and tectonic reconstructions. *Journal of Geophysical Research* 111, B08401.

566 Hey, R.N., Wilson, D.S., 1982. Propagating rift explanation for the tectonic evolution of the northeast
567 Pacific—The pseudomovie. *Earth and Planetary Science Letters* 58, 167-184.

568 Hey, R.N., 1977. A new class of "pseudofaults" and their bearing on plate tectonics: A propagating rift
569 model. *Earth and Planetary Science Letters* 37, 321-325.

570 Hey, R.N., 2004. Propagating Rifts and Microplates at Mid-Ocean Ridges, in: Selley, R.C., Cocks, R.,
571 Plimer, I. (Eds.), *Encyclopedia of Geology*. Academic Press, London, pp. 396-405.

572 Hey, R.N., Duennebier, F.K., Morgan, W.J., 1980. Propagating rifts on midocean ridges. *J. Geophys. Res.*
573 85, 3647-3658.

574 Hey, R.N., Menard, H.W., Atwater, T.M., Caress, D.W., 1988. Changes in direction of seafloor spreading
575 revisited. *Journal of Geophysical Research* 93, 2803-2811.

576 Hey, R.N., Naar, D.F., Kleinrock, M.C., Phipps Morgan, W.J., Morales, E., Schilling, J.G., 1985. Microplate
577 tectonics along a superfast seafloor spreading system near Easter Island. *Nature* 317, 320-325.

578 Klootwijk, C.T., Gee, J.S., Peirce, J.W., Smith, G.M., McFadden, P.L., 1992. An early India-Asia contact:
579 paleomagnetic constraints from Ninetyeast ridge, ODP Leg 121. *Geology* 20, 395-398.

580 Krishna, K.S., Abraham, H., Sager, W.W., Pringle, M.S., Frey, F., Gopala Rao, D., Levchenko, O.V., 2012.
581 Tectonics of the Ninetyeast Ridge derived from spreading records in adjacent oceanic basins and age
582 constraints of the ridge. *Journal of Geophysical Research* 117, B04101.

583 Krishna, K.S., Rao, D.G., Ramana, M.V., Subrahmanyam, V., Sarma, K.V.L.N.S., Pilipenko, A.I.,
584 Shcherbakov, V.S., Murthy, I.V.R., 1995. Tectonic model for the evolution of oceanic crust in the
585 northeastern Indian Ocean from the Late Cretaceous to the Early Tertiary. *Journal of Geophysical*
586 *Research* 100, 20011-20024.

587 Lee, T.-Y., Lawver, L.A., 1995. Cenozoic plate reconstruction of Southeast Asia. *Tectonophysics* 251, 85-
588 138.

589 Livermore, R., Balanyá, J.C., Maldonado, A., Martínez, J.M., Rodríguez-Fernández, J., de Galdeano, C.S.,
590 Zaldívar, J.G., Jabaloy, A., Barnolas, A., Somoza, L., Hernández-Molina, J., Suriñach, E., Viseras, C., 2000.
591 Autopsy on a dead spreading center: The Phoenix Ridge, Drake Passage, Antarctica. *Geology* 28, 607-
592 610.

593 MacDonald, K.C., Scheirer, D.S., Carbotte, S.M., 1991. Mid-ocean ridges: Discontinuities, segments and
594 giant cracks. *Science* 253, 986.

595 Mammerickx, J., Klitgord, K.D., 1982. Northern East Pacific Rise: Evolution from 25 m.y. B.P. to the
596 present. *Journal of Geophysical Research* 87, 6751-6759.

597 Mammerickx, J., Naar, D.F., Tyce, R.L., 1988. The Mathematician Paleoplate. *Journal of Geophysical*
598 *Research* 93, 3025-3040.

599 Matthews, K.J., Müller, R.D., Wessel, P., Whittaker, J.M., 2011. The tectonic fabric of the ocean basins.
600 *Journal of Geophysical Research* 116, B12109.

601 Molnar, P., Tapponnier, P., 1975. Cenozoic tectonics of Asia: effects of a continental collision. *Science*
602 189, 419-426.

603 Montelli, R., Nolet, G., Dahlen, F.A., Masters, G., Engdahl, E.R., Hung, S.H., 2004. Finite-frequency
604 tomography reveals a variety of plumes in the mantle. *Science* 303, 338.

605 Müller, R.D., Sdrolias, M., Gaina, C., Roest, W.R., 2008. Age, spreading rates, and spreading asymmetry
606 of the world's ocean crust. *Geochemistry, Geophysics, Geosystems* 9, Q04006.

607 Naar, D.F., Hey, R.N., 1989. Speed limit for oceanic transform faults. *Geology* 17, 420-422.

608 NOAA National Centers for Environmental Information (2004): Multibeam Bathymetry Database
 609 (MBBDB), Sojourn Expedition Leg 4, R/V Melville, 1997. NOAA National Centers for Environmental
 610 Information. doi:10.7289/V56T0JNC accessed on 14 July 2015.
 611 O'Neill, C., Müller, D., Steinberger, B., 2005. On the uncertainties in hot spot reconstructions and the
 612 significance of moving hot spot reference frames. *Geochemistry, Geophysics, Geosystems* 6.
 613 Ogg, J.G., 2012. Geomagnetic Polarity Time Scale, in: Gradstein, F.M., Ogg, J.G., Schmitz, M., Ogg, G.
 614 (Eds.), *The Geologic Time Scale 2012*. Elsevier, Oxford, UK, p. 1176.
 615 Patriat, P., Achache, J., 1984. India-Eurasia collision chronology has implications for crustal shortening
 616 and driving mechanism of plates. *Nature* 311, 615-621.
 617 Phipps Morgan, J., Parmentier, E.M., 1985. Causes and rate-limiting mechanisms of ridge propagation:
 618 a fracture mechanics model. *Journal of Geophysical Research* 90, 8603-8612.
 619 Phipps Morgan, J., Sandwell, D.T., 1994. Systematics of ridge propagation south of 30 S. *Earth and*
 620 *Planetary Science Letters* 121, 245-258.
 621 Replumaz, A., Karason, H., van der Hilst, R.D., Besse, J., Tapponnier, P., 2004. 4-D evolution of SE Asia's
 622 mantle from geological reconstructions and seismic tomography. *Earth and Planetary Science Letters*
 623 221, 103-115.
 624 Ribe, N.M., Delattre, W.L., 1998. The dynamics of plume—ridge interaction—III. The effects of ridge
 625 migration. *Geophysical Journal International* 133, 511-518.
 626 Rowley, D.B., 1998. Minimum Age of Initiation of Collision between India and Asia North of Everest
 627 Based on the Subsidence History of the Zhepure Mountain Section. *The Journal of Geology* 106, 220-
 628 235.
 629 Sandwell, D.T., Müller, R.D., Smith, W.H., Garcia, E., Francis, R., 2014. New global marine gravity model
 630 from CryoSat-2 and Jason-1 reveals buried tectonic structure. *Science* 346, 65-67.
 631 Schouten, H., Klitgord, K.D., Gallo, D.G., 1993. Edge-driven microplate kinematics. *Journal of*
 632 *Geophysical Research* 98, 6689-6701.

633 Searle, M.P., Windley, B.F., Coward, M.P., Cooper, D.J.W., Rex, A.J., Rex, D., Tingdong, L., Xuchang, X.,
634 Jan, M.Q., Thakur, V.C., Kumar, S., 1987. The closing of the Tethys and the tectonics of the Himalaya.
635 Geological Society of America Bulletin 98.

636 Searle, R.C., Bird, R.T., Rusby, R.I., Naar, D.F., 1993. The development of two oceanic microplates:
637 Easter and Juan Fernandez microplates, East Pacific Rise. Journal of the Geological Society 150, 965-
638 976.

639 Ségoufin, J., Munschy, P., Bouysse, P., Mendel, V., Grikurov, G., Leitchenkov, G., Subrahmanyam, C.,
640 Chand, S., Pubellier, S., Patriat, P., 2004. Map of the Indian Ocean (1:20 000 000), sheet 1:
641 “Physiography”, sheet 2: “Structural map”. Commission for the Geological Map of the World, Paris.

642 Seton, M., Müller, R.D., Zahirovic, S., Gaina, C., Torsvik, T.H., Shephard, G., Talsma, A., Gurnis, M.,
643 Turner, M., Maus, S., Chandler, M., 2012. Global continental and ocean basin reconstructions since 200
644 Ma. Earth-Science Reviews 113, 212-270.

645 Seton, M., Whittaker, J.M., Wessel, P., Müller, R.D., DeMets, C., Merkouriev, S., Cande, S., Gaina, C.,
646 Eagles, G., Granot, R., 2014. Community infrastructure and repository for marine magnetic
647 identifications. Geochemistry, Geophysics, Geosystems 15, 1629-1641.

648 Small, C., 1995. Observations of ridge - hotspot interactions in the Southern Ocean. Journal of
649 Geophysical Research 100, 17931-17946.

650 Tebbens, S.F., Cande, S.C., 1997. Southeast Pacific tectonic evolution from Early Oligocene to Present.
651 Journal of Geophysical Research 102, 12061-12084.

652 Tebbens, S.F., Cande, S.C., Kovacs, L., Parra, J.C., LaBrecque, J.L., Vergara, H., 1997. The Chile ridge: a
653 tectonic framework. Journal of Geophysical Research 102, 035-012.

654 Van der Voo, R., Spakman, W., Bijwaard, H., 1999. Tethyan subducted slabs under India. Earth and
655 Planetary Science Letters 171, 7-20.

656 van Hinsbergen, D.J.J., Lippert, P.C., Dupont-Nivet, G., McQuarrie, N., Doubrovine, P.V., Spakman, W.,
657 Torsvik, T.H., 2012. Greater India Basin hypothesis and a two-stage Cenozoic collision between India
658 and Asia. Proceedings of the National Academy of Sciences 109, 7659-7664.

Wessel, P., Smith, W.H.F., Scharroo, R., Luis, J., Wobbe, F., 2013. Generic Mapping Tools: Improved Version Released. *Eos, Transactions American Geophysical Union* 94, 409-410.

Whittaker, J.M., Afonso, J.C., Masterton, S., Müller, R.D., Wessel, P., Williams, S.E., Seton, M., 2015. Long-term interaction between mid-ocean ridges and mantle plumes. *Nature Geoscience* 8, 479-483.

Whittaker, J.M., Williams, S.E., Müller, R.D., 2013. Revised tectonic evolution of the Eastern Indian Ocean. *Geochemistry, Geophysics, Geosystems* 14, 1891-1909.

Whittaker, J.M., Müller, R.D., Leitchenkov, G., Stagg, H., Sdrolias, M., Gaina, C., Goncharov, A., 2007. Major Australian-Antarctic plate reorganization at Hawaiian-Emperor bend time. *Science* 318, 83-86.

Zahirovic, S., Müller, R.D., Seton, M., Flament, N., Gurnis, M., Whittaker, J., 2012. Insights on the kinematics of the India-Eurasia collision from global geodynamic models. *Geochemistry Geophysics Geosystems* 13.

Figure 1.

VGG maps (Sandwell et al., 2014) of the eastern/southeastern Indian Ocean basin, showing key seafloor structures that were mapped using the VGG data and described in Section 4. These include two pseudofaults (PF), an extinct ridge (ER), a microplate (MP) — the ‘Mammerickx Microplate’ (see Section 5), abyssal hill fabric (AHF), and ‘migrating offset fabric’ (MOF) comprising ‘W’ shaped lineations produced by back and forth ridge propagation. Several fracture zones are also labeled A, B, C, E1 and E2 (also shown in Figure 3). (a) Regional map with large igneous provinces (from Whittaker et al., 2015) shown in transparent orange, and the ship track segments from Figure 5 in yellow (Sojourn Expedition Leg 4, R/V Melville, 1997). An orange star identifies the location at the Southeast Indian Ridge where spreading rates were calculated using the Euler rotation poles of Cande and Patriat (2015). (b-c) Zoomed in maps of the Antarctic Plate north of the Kerguelen Plateau (KP), and the Indian Plate west of the Ninetyeast Ridge (NER), respectively, showing magnetic anomaly picks of Cande et al. (2010). Traces of the seafloor lineations produced by back and forth ridge propagation (dashed white lines), that make up the ‘chaotic seafloor’ from a, are offset from their negative gravity anomalies so as not to obscure their signal. The Mammerickx Microplate is shaded green. BR, Broken Ridge.

687

688 Figure 2.

689 VGG map (Sandwell et al., 2014) of the eastern Pacific Ocean basin, showing active and extinct
690 microplates (transparent green). The Pacific-Antarctic Ridge and East Pacific Rise produce positive
691 VGG anomalies, while the Chile Ridge produces a negative VGG anomaly. B, Bauer Microplate (extinct);
692 E, Easter Microplate (active); F, Friday Microplate (extinct); H, Hudson Microplate (extinct); JF, Juan
693 Fernandez Microplate (active); M, Mathematician Microplate (extinct); S, Selkirk Microplate (extinct).

694

695 Figure 3.

696 A chron 18n.2n (40.1 Ma) reconstruction, in an India-fixed reference frame, of (a) the VGG data
697 (Sandwell et al., 2014), and (b) the magnetic anomaly picks and tectonic fabric traces. The plate
698 reconstruction software *GPlates* (Boyden et al., 2011) was used to reconstruct the data using the Seton
699 et al. (2012) global plate reconstruction model. Magnetic anomaly picks are from Cande et al. (2010)
700 (circles) and Ségoufin et al. (2004) (stars). Fracture zone traces are from Matthews et al. (2011). Plate
701 boundaries are continuous dark orange lines; the Australian-Antarctic plate boundary is represented
702 by a dashed line as it may have been a diffuse boundary at this time (Whittaker et al., 2013). Spreading
703 (white on black lines) and transform (solid black lines) segments of the extinct ridge have been
704 distinguished from the VGG data. Several key fracture zones are labeled A-E2 in (a). ANT-IND MOR,
705 Australian-Antarctic mid-ocean ridge; AUS-ANT DB, Australian-Antarctic diffuse boundary; AUS-IND
706 TFB, Australian-Indian transform boundary; K, Kerguelen Plateau; NER, Ninetyeast Ridge; MP,
707 microplate.

708

709 Figure 4.

710 3-D perspective VGG map of the microplate and region of chaotic seafloor to the north, draped over the
711 SRTM30 Plus V11.0 digital elevation model (Becker et al., 2009). Along the southern map boundary a
712 horizontal plane has been inserted at 4 km depth. The white dashed line separates chaotic undulate
713 seafloor in the east (to the north of the microplate and west of the Ninetyeast Ridge, NER), from
714 relatively flat seafloor immediately to the west. Fracture zones are also largely absent from the

715 seafloor to the east of the dashed line, rather 'W' shaped lineations produced by migrating spreading
716 ridge offsets (MO) are dominant. ER, extinct ridge; FSF, flat seafloor; FZ C, fracture zone C (see Figures
717 1a and 3); MP, microplate; NER, Ninetyeast Ridge; PF, pseudofault; USF, undulate seafloor.

718

719 Figure 5.

720 Multibeam bathymetry (Sojourn Expedition Leg 4, R/V Melville, 1997) collected north of the identified
721 extinct ridge (ER), highlighting changes in the orientation of abyssal hills (see Figure 1 for location).
722 Black and white lines indicate the orientation of the abyssal hills. Adjacent to fracture zone C (FZ C)
723 they are oriented $\sim 90\text{-}95^\circ$ (a), while adjacent to fracture zone D (FZ D) (b) and closer to the extinct
724 ridge trace (a) they are oriented $\sim 110\text{-}120^\circ$.

725

726 Figure 6.

727 Schematic reconstruction of the formation of the Mammerickx Microplate (MM). (a) Chron 22n time
728 (49.3 Ma) precedes microplate formation. At this time there is $\sim$ north-south directed spreading
729 between the Indian and Antarctic plates, and to the east of fracture zone C the Indian-Antarctic ridge
730 likely comprised non-transform offsets. (b) At approximately chron 21n(o) time (47.3 Ma) a
731 reorganisation at the Indian-Antarctic ridge initiates, involving ridge propagation from a non-
732 transform offset, and the establishment of three transform faults at the ridge (fracture zones D, E1 and
733 E2). (c) Dual spreading at the newly establishing southerly ridge and the pre-existing northerly ridge
734 occurs for a short period, approximately throughout chron 21n time (47.3 – 45.7 Ma). During
735 formation of the Mammerickx Microplate the pre-existing northerly ridge lengthens in an easterly and
736 southerly direction and curves inwards towards the microplate core leaving behind counterclockwise
737 rotated abyssal hills. Rotation of the ridge is also reflected in the curvature of fracture zone D. (d) Dual
738 spreading has likely ceased and the microplate has detached after chron 20n(o) time (43.4 Ma).
739 Volcanism associated with the Kerguelen Plateau (K) and Ninetyeast Ridge (NER), attributed to the
740 Kerguelen Plume is shown in purple. Transform (TF) offsets are green lines, and non-transform offsets
741 are dashed magenta lines. The extinct northerly ridge is gray in (d). See Figure 3 for the locations of
742 fracture zones C, D, E1 and E2. MOR, mid-ocean ridge; TJ, triple junction.

Figure 1a

Figure 1b-c

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Table 1

Approximate distance between the Kerguelen Hotspot and the initiation point of the pseudofaults.

Reference frame	Distance to hotspot centre point* (edge of 400 km plume radius^)
Fixed hotspot	1090 km (690 km)
O'Neill et al. (2005), moving hotspot	650 km (250 km)
Dobrovine et al. (2012), moving hotspot	820 km (420 km)

*Hotspot location (69°E, 49°S) from Whittaker et al. (2015)

^Choice of 400 km plume radius is from Montelli et al. (2004)