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Active Faulting on the Ninetyeast Ridge and its Relation to Deformation of the Indo-Australian Plate

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Abstract

The ~4500 km-long Ninetyeast Ridge (NER) in the northeastern Indian Ocean crosses a broad zone of deformation where the Indo-Australian plate is fracturing into three smaller plates (India, Capricorn, Australia) separated by diffuse boundaries whose extents are poorly defined. New multichannel seismic reflection profiles image active faults along the entire length of the NER and show spatial changes in the style of deformation along the ridge. The northern NER (0-5°N) displays transpressional motion along WNW-ESE faults. Observed fault patterns confirm strike-slip motion at the western extent of the April 2012 Wharton Basin earthquake swarm. In the central NER (5-8°S), deformation on WNW-ESE-trending thrust faults implies nearly N-S compression. An abrupt change in fault style occurs between 8° and 11°S, with modest, extension characterizing the southern NER (11-27°S). Although extension is dominant, narrow zones of faults with strike-slip or compressional character also occur in the southern NER, suggesting a complex combination of fault motions. At all sites, active faulting is controlled by the reactivation of original, spreading-center formed, normal faults, implying that deformation is opportunistic and focused along existing zones of weakness, even when original fault trend is oblique to the direction of relative plate motion. Observed faulting can be interpreted as India-Australia deformation in the northern NER and Capricorn-Australia deformation in the southern NER. The India-Capricorn boundary is directly adjacent to the northern NER and this juxtaposition combined with a different style of faulting to the east of the NER imply that the ridge is a tectonic boundary.

1. Introduction

The vast Indo-Australian plate in the central Indian Ocean is breaking into three smaller pieces separated by diffuse boundaries (Fig. 1) [*Royer and Gordon, 1997*]. Although this location is perhaps the best-documented distributed deformation within an oceanic plate [*Gordon, 2000*], many details are lacking owing to the large extent and remote location of the affected area. Compressional faults and folds occur in the Central Indian Basin south of India and west of the Ninetyeast Ridge (NER) [*Weissel et al., 1980; Petroy and Wiens, 1989; Bull and Scrutton, 1992; Krishna et al., 2001; Delescluse and Chamot Rooke, 2007*]. In contrast, deformation is mainly by strike-slip faulting in the Wharton Basin to the east of the NER [*Petroy and Wiens, 1989; Stein et al., 1989; Deplus et al., 1998; Deplus, 2001*]. In the middle of this deformed zone, the NER is a long (~4500 km) volcanic ridge that displays active seismicity in some locations, but the nature of deformation is unclear because geophysical data are sparse in the region. If the NER is only a passive weal on the oceanic lithosphere, it may simply respond to broad-scale tectonic forces with little change to the pattern of faulting extending from adjacent basins. Alternatively, it has been suggested that the NER is a mechanical boundary owing to the apparent change in deformation across it [*e.g., Delescluse and Chamot-Rooke, 2007*], so faulting may be complex. We examined new multichannel seismic reflection profiles and multibeam bathymetry data from the NER to understand its role in the fracturing of the Indo-Australian plate. We find evidence of active faulting of variable style along its entire length. In this report, we document this faulting and explore implications for the location and style of diffuse plate boundaries.

1.1 Tectonic Development of the Indo-Australian Plate and Formation of the NER

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63   The Indo-Australian plate is a Cenozoic amalgamation of two pre-existing plates,

64   India and Australia. During the rifting of Gondwana, both plates formed on the north

65   side of spreading ridges that separated the northward-drifting continents from Antarctica

66   [*Norton and Sclater, 1979*]. Because both plates drifted almost exactly northward

67   relative to Antarctica and have not rotated significantly, the Indo-Australian plate

68   contains many fracture zones trending approximately N-S with nearly E-W trending

69   magnetic anomalies in between. India and Australia continued as separate plates until the

70   time of anomaly 19 (~42 Ma [*Cande and Kent, 1995*]) when the Wharton Ridge (located

71   east of the NER, separating India and Australia) jumped southward to form the

72   continuous Southeast Indian Ridge [*Royer et al., 1991*; *Krishna et al., 1995*]. At that

73   time, the India and Australia plates were combined.

74   The NER trends nearly N-S and stretches from 31°S at Broken Ridge to 10°N,

75   where it disappears beneath sediments of the Bengal Fan (Fig. 1). Magnetic lineation

76   breaks and satellite altimetry data show that the NER is nearly parallel to fracture zones

77   formed at a paleo-spreading ridge that once separated the India and Australia plates

78   [*Royer and Sandwell, 1989; Krishna et al., 1995; 2012*]. Many different authors have

79   explained the formation of the NER as a result of various tectonic anomalies [see review

80   by *Royer et al., 1991*], but the modern consensus is that it was created by hotspot

81   volcanism that emplaced a ridge on the northward drifting Indian plate from Late

82   Cretaceous to early Cenozoic time *[Royer et al., 1991; Krishna et al., 2012]*. The hotspot

83   was often located near the spreading ridge [*Sager et al., 2010; Krishna et al., 2012*] and

84   changes in NER morphology may be related to the proximity of the hotspot to the

85 spreading ridge [*Royer et al., 1991*]. Because of its near-ridge location, the hotspot

86 emplaced material on both the Indian and Antarctic plates, with most of the volcanic

87 product ending up on the India plate owing to repeated southward ridge jumps [*Krishna*

88 *et al., 2012*]. Nevertheless, the hotspot volcanism produced a remarkably linear age

89 progression that ranges from 77 Ma at Ocean Drilling Program (ODP) Site 758, in the

90 northern NER, to 43 Ma at Deep Sea Drilling Project (DSDP) Site 254 in the southern

91 NER [*Krishna et al., 2012*]. At ~42 Ma, the large-scale reorganization of spreading

92 centers that brought together the India and Australia plates also moved the hotspot

93 permanently beneath the Antarctic plate, ceasing the NER formation [*Royer et al., 1991;*

94 *Krishna et al., 2012*].

95 **1.2 Diffuse Plate Boundaries in the Central Indian Ocean**

96   Plate geometry, seafloor spreading data, and differences in crustal gravity lineations

97 indicate that the northern NER is the location of a diffuse triple junction [*Royer and*

98 *Gordon, 1997*] (Fig. 1). Because this triple junction implies that three wide plate

99 boundaries come together, each with different stress fields, different styles of

100 deformation are expected along the NER as it traverses these boundary zones.

101   Euler poles describing relative plate motions occur within two of the diffuse

102 boundaries and as a result, the style of deformation changes along each of these

103 boundaries from extension to compression [*Gordon, 2000*]. The India-Capricorn Euler

104 pole is located near the equator, close to the Chagos-Laccadive Ridge (Fig. 1) [*Royer and*

105 *Gordon, 1997; DeMets et al., 2010*], implying compression south of India and extension

106 between the Chagos-Laccadive Ridge and the Carlsberg Ridge. The Capricorn-Australia

107 pole is located at the southern end of the NER [*Royer and Gordon, 1997; DeMets et al.,*

108 *2010*], implying a zone of extension from the Southeast Indian Ridge (SEIR) to the

109 southern NER and compression farther north.   In contrast, only compression is expected

110 along the India-Australia boundary, located southwest of the Java Trench, because the

111 Euler pole describing that plate pair is situated in the Central Indian Basin, ~1000 km

112 away from that boundary [*Royer and Gordon, 1997; DeMets et al., 2010; Bull et al.,*

113 *2010*].

114   South of India, distributed deformation occurs within the India-Capricorn plate

115 boundary and is characterized by E-W thrust faults spaced 5-10 km apart and long

116 wavelength (100-300 km) folds [*Weissel et al., 1980;Wiens et al., 1986; Bull and*

117 *Scrutton, 1992*]. The thrust faults result from nearly N-S compression reactivating nearly

118 E-W normal faults that were formed in the ocean crust by seafloor spreading [*Bull and*

119 *Scrutton, 1992*]. This deformation extends across a broad zone to the west side of the

120 NER (Fig. 1) and began 14-18 Myr ago [*Krishna et al., 2009; Bull et al., 2010*].

121   Earthquakes and seismic reflection profiles in the Wharton Basin imply that it is

122 broken into narrow slivers by reactivation of the nearly N-S trending fracture zones by

123 left-lateral strike-slip motion [*Delescluse and Chamot Rooke, 2007; Deplus et al., 1998;*

124 *Deplus, 2001*].   The lateral extent of this reactivation is unclear but has been observed in

125 geophysical data near the equator [*Deplus et al., 1998*] and in the form of strike-slip

126 earthquakes along fracture zones in the wedge between the Java Trench and the NER

127 [*Delescluse and Chamot Rooke, 2007; Satriano et al., 2012*]. Although a few NE-SW

128 trending gravity lineations are observed in this region perpendicular to the convergent

129 plate motion direction [*Petroy and Wiens, 1989; Stein et al., 1990*], the trend of

130 reactivated fracture zones is oblique to the direction of compressive stress and

131 presumably this mismatch between stress and fault direction is a result of opportunistic

132 fracturing along inherited zones of weakness caused by original crustal faults.

133   Few earthquakes occur along the southern NER and faulting is poorly documented in

134 this region, so deformation on the Capricorn-Australia boundary is unclear and the

135 boundary may be as much as 2000 km in width [*DeMets et al., 2010*]. The nature of this

136 boundary in the vicinity of the NER south of the equator is simply not known.

137 **1.3 Seismicity in the Vicinity of the NER**

138   Earthquakes occur in a diffuse zone across the Central Indian Basin and Wharton

139 Basin from ~35°S to ~7°N (Fig. 2) [e.g., *Delescluse and Chamot Rooke, 2007*]. The

140 greatest seismic activity occurs in a band stretching NE-SW from the Java Trench, across

141 the northern NER, into the Central Indian Basin south of India. Near the Java Trench,

142 events are mainly NE thrust faults related to subduction. In the Central Indian Basin, near

143 the equator, these events also display dominantly thrust focal mechanisms, but oriented

144 N-S with some strike-slip mechanisms mixed in (Fig. 2). This pattern is thought to result

145 from compression between the India and Capricorn plates, with thrusting taking place

146 where original normal faults in the oceanic crust are reactivated and strike-slip events

147 occurring on N-S-trending fracture zones [*Petroy and Wiens, 1989; Bull and Scrutton,*

148 *1990; Delescluse et al., 2008*].

149   South of ~5°S, earthquakes define a sparse NE-SW oriented band that includes the

150 NER. As a result, earthquakes in the Wharton Basin are observed to the north of ~17°S

151 whereas those in the Central Indian Basin are mainly south of ~18°S (Fig. 2). Strike-slip

152 focal mechanisms with WNW-ESE/ENE-WSW nodal planes dominate in the northern

153 Wharton Basin [*Petroy and Wiens, 1989; Royer and Gordon, 1997*]. They occur mostly

7

154   in the wedge-shaped area from the northern NER to the Java Trench and south to ~15°S

155   and are thought to result mainly from Late Cretaceous and early Cenozoic fracture zones

156   that have been reactivated as left-lateral strike-slip faults [*Deplus et al., 1998; Deplus,*

157   *2001; Delescluse et al., 2012*]. Some of these earthquakes have been remarkably strong

158   for oceanic earthquakes [e.g., *Robinson et al., 2001*], including a Mw 7.9 shock in 2000

159   and two recent tremors, Mw 8.6 and 8.2, that occurred on 11 April 2012 [*Satriano et al.,*

160   *2012; McGuire and Beroza, 2012; Meng et al., 2012*]. South of ~10°S, focal

161   mechanisms indicate mostly strike-slip and thrust faults, with the former having similar

162   nodal planes to strike-slip mechanisms farther north and the latter showing NW-SE

163   convergence (Fig. 2). At about 10°S, a few thrust focal mechanisms are observed in the

164   Wharton Basin (Fig. 2) near a low SW-NE trending ridge that parallels gravity lineations.

165   These mechanisms may indicate thrust faulting along that feature. A small number of

166   extensional focal mechanisms occur to the southwest of the NER (mostly farther south

167   than the extent of Figure 2), caused by divergence south of the Capricorn-Australia Euler

168   pole [*Royer and Gordon, 1987*].

169   Northern NER earthquakes display similar strike-slip mechanisms to nearby

170   Wharton Basin earthquakes and because the nearly N-S nodal plane is close to the trend

171   of the NER, it was proposed that ENE-WSW strike-slip faults occur along the NER

172   [*Stein and Okal, 1978*]. The seismic energy radiation pattern and aftershock distribution

173   of the 2012 Wharton Basin events indicate that faulting in the northern Wharton Basin

174   and NER is more complex [*Satriano et al., 2012; McGuire and Beroza; 2012; Delescluse*

175   *et al., 2012; Meng et al, 2012*]. Although the two main shocks of this cluster align with

176   the expected trend of original Wharton Basin fracture zones, it appears that the

177 earthquake swarm activated a lattice of WNW-ESE right lateral strike-slip faults [*Meng*

178 *et al., 2012*]. The aftershocks included the northern NER and imply nearly E-W strike-

179 slip faults in that area [*Meng et al., 2012*].

180 **1.4 Faulting on the NER**

181   Given the diffuse deformation and seismicity in the area, faulting is expected on the

182 NER. Most published observations of NER faults are isolated examples that do not give

183 a comprehensive picture [*Veevers, 1974; Naini and Eittreim, 1974; Curray and*

184 *Munashinge, 1989; Shipboard Scientific Party, 1989a, 1989b*]. Virtually all faults

185 reported in prior publications appear to be normal, except for one profile that apparently

186 shows thrust faults on the east side of the southern NER near DSDP Site 214 [*Pilipenko,*

187 *1996*]. E-W trending normal faults have been reported along the length of the NER

188 [*Pilipenko, 1996; Sager et al., 2010*]. They often form rotated fault blocks and grabens

189 and were probably formed by tension near the spreading ridge during NER formation

190 [*Sager et al., 2010*].

191 **2. Data and Methods**

192   High-resolution multibeam bathymetry data and 10-fold multichannel seismic

193 (MCS) profiles were collected over the NER during cruise KNOX06RR of the R/V

194 *Roger Revelle* [Sager et al., 2007]. Multibeam data were acquired using a 12 kHz

195 Kongsberg Simrad EM120 sonar system, which yielded swaths of data 10-30 km in

196 width, allowing detailed imaging of the seafloor at the survey sites.

197   More than 3700 km of MCS data were collected at six sites, four of which are

198 coincident with ODP or DSDP drill sites (Sites 214, 216, 253, and 758). The seismic

199 system used a 48-channel hydrophone array (streamer) and the source consisted of two

200 generator-injector (GI) airguns with generator volumes of 45 in^3 (737 cm^3) and injector

201 volumes of 105 in^3 (1720 cm^3). Seismic data were processed to CDP stack and time

202 migration was produced assuming a single velocity of 1500 ms^{-1}.

203   "Acoustic basement" was recognized as a strong (high acoustic impedance

204 contrast), widespread reflector beneath which seismic returns were absent, incoherent, or

205 reflectors were intermittent. Throughout much of the study area, acoustic basement was a

206 sharp, well-defined horizon. At a few locations, acoustic basement was absent or

207 extended in depth (i.e., a thick package of reflections) with an appearance similar to

208 sediments in places, perhaps indicating the seismic waves did not reach the igneous pile.

209 In most cases the acoustic basement horizon likely represents the top of the igneous rock

210 beneath the sedimentary section. However, in places where the horizon is thick or has

211 sedimentary characteristics, basement may be volcaniclastic sediments, such as the thick

212 section of volcanic ash cored at DSDP Site 253 [*Shipboard Scientific Party, 1974*].

213   Faults were recognized by vertical offsets or discontinuities of sedimentary layers,

214 monoclinal folds, bowing or kinking of sedimentary layers, coherent diffractions cutting

215 sediment horizons, narrow troughs with sediment fill, and narrow grabens. Some faults

216 show extensive deformation over an extended area and are probably the result of fault

217 zones with a number of smaller faults that cannot be recognized individually. Active

218 faults were recognized by the fact that they extend through the sedimentary section from

219 basement to the surface, either causing a seafloor offset or disturbance of recent

220 sediments.

221   Because of the wide spacing of survey sites, we searched for older seismic data

222 that show faults in the NER. Somewhat useful data were collected on three cruises of the

223 R/V *Robert Conrad* during 1986 that surveyed ODP drill sites (cruises RC2705, RC2707,

224 and RC2708). A single channel streamer was used as the receiver and a single 80 in^3

225 (1320 cm^3) water gun was used as a source [*Newman and Sclater, 1988*]. Analog seismic

226 profiles from these cruises were obtained from Lamont Doherty Earth Observatory. In

227 addition, a small amount of similar single-channel seismic data collected during ODP

228 Leg 121 was also examined at Site 757 [*Shipboard Scientific Party, 1989a; 1989b*].

229 **3. NER Fault Observations**

230 Faults were interpreted by observing diagnostic features in seismic sections as

231 described in the previous section and are shown in figures by symbols on bathymetry

232 maps and in seismic sections by arrows that indicate the locations of fault traces near the

233 seafloor. In this section we describe the types of motion inferred from the observed

234 faults. Owing to inadequate imaging or ambiguous geometry, it was not possible to

235 interpret the motions of all faults (usually shown by gray arrows in the figures).

236 **3.1 Site 758 (5.2°N)**

237 Site 758 multibeam bathymetry data cover the southern end of a large seamount

238 and two small seamounts to its south (Fig. 3). These data clearly image the fractured

239 nature of the seafloor in the vicinity of the two small seamounts. Approximately 10

240 bathymetric lineations striking WNW-ESE (~N100°E) are observed crossing almost the

241 entire multibeam data set (Fig. 3). These lineations appear to be small ridges and/or

242 escarpments, often with paired troughs. Bathymetric contours have a "jagged"

243 appearance, with sharp, nearly right angle offsets of 3-10 km in many places (Fig. 3).

244 These displacements give the appearance that the bathymetric features have been offset.

245   Notably, the two small seamounts have nearly N-S trending flank contours that appear to

246   have been offset by ~10 km along the lineation in between them.

247   Seismic data show that the NER near Site 758 is extensively faulted (Fig. 4).

248   Faults are apparent on N-S trending seismic lines but are rarely noted on E-W oriented

249   seismic lines, implying that the faults trend nearly E-W, as do the bathymetric lineations.

250   The bathymetric lineations correspond to major faults that show significant offset at the

251   seafloor (e.g., faults 1-2, 6-7, 8; numbers in Fig. 4).

252   Observed faulting at Site 758 implies both compression and strike-slip motion.

253   Compression is indicated by the upwarp of layers (between faults 1-2 and 4-5) and up-

254   thrust acoustic basement ("pop-up") features such as the small block between faults 6-7

255   and the asymmetric ridge at fault 8. Compression also explains the geometry of fault 3,

256   which shows a break in sediment layers that are upturned at the fault.

257   Strike-slip motion is implied by faults that separate sedimentary sections of

258   different thickness and different seismic character, as observed across faults 1-2. In

259   addition, this fault pair is likely a flower structure because the faults appear to converge

260   at depth. Strike-slip motion is also implied by the observed offsets in bathymetric

261   contours.

262   Two of the active Site 758 faults connect with offsets of acoustic basement (faults

263   2, 8). It is difficult to determine whether active faulting is the cause of the offsets

264   because the overlying sediment cover is too thin to compare the sedimentary and

265   basement offsets.

266   Cruise RC2705 seismic data cover a broader area than the KNOX06RR survey

267   and show that faulting is widespread, being observed on all seismic lines (Fig. 5). Where

268   the RC2705 data overlap the multibeam bathymetry, bathymetric lineations correlate with

269   faults (Fig. 4). The resolution of these older data is mediocre and it is difficult to discern

270   details of the faults below the seafloor. Most are recognized only by notches or offsets of

271   the seafloor; although, fault 1 (Fig. 6) displays an asymmetric basement block uplift like

272   that of fault 8 in Figure 4.

273   **3.2 Site 216 (1.5°N)**

274   Multibeam bathymetry data at Site 216 (Fig. 7) show lineations with WNW-ESE

275   trends (~N100°E to N110°E) stretching across the top and east flank of a large seamount.

276   These lineations are mostly troughs incising the sediments. In addition, contours on the

277   eastern flank of the seamount appear jagged, with right angle (mostly left lateral) offsets

278   of a few kilometers, often occurring where intersected by the bathymetric lineations.

279   Seismic sections show that the bathymetric lineations correspond to larger, active faults

280   (faults 2, 3, 5-6, 8; numbers in Fig. 8). Faults are seen most clearly on N-S oriented lines

281   but also are detected on lines with other orientations, consistent with the orientation of

282   the nearly E-W bathymetry lineations.

283   Site 216 faulting has similar characteristics to that of Site 758, indicating both

284   compression and strike-slip motion. Compression is indicated by fault 7, which has

285   reversed geometry and occurs at the south edge of a basement pop-up block. Other

286   evidence for compression is the upwarp of sediment layers and acoustic basement

287   observed north of fault 3, between faults 5-6, 9-10, and at fault 8. Fault 3 displays a

288   sharp kink in sediment layering, which may have the same cause.

13

289   The highly-deformed sag trough of fault 2 is a structure commonly observed on

290   strike slip faults. In addition, the sediment layers across this fault have different

291   thicknesses, indicating lateral motion. Sedimentary layers also change thickness and

292   character across faults 4, 7, 8, and 10, likewise implying lateral movements. In the case

293   of fault 8, this observation implies that both reverse and strike-slip motion occurred.

294   Strike-slip faulting is also consistent with the observation of laterally-offset bathymetry

295   contours.

296   Offsets of acoustic basement are observed for faults 1, 6, and 7. For the latter

297   two, the acoustic basement offset is larger than the sediment offset, indicating that an

298   older basement fault was reactivated. For fault 1, the offset of acoustic basement and

299   sediment layers is approximately the same, implying that faulting at later stage caused the

300   acoustic basement to develop an offset.

301   **3.3 Site NER2 (6.7°S)**

302   Site NER2 encompasses most of a flat-topped seamount with shallow valleys

303   across its top, a steep western flank, and a shallow eastern flank that extends eastward out

304   of the survey (Fig. 9). E-W bathymetric lineations also occur at this site; however, they

305   are not as distinct as at Sites 216 and 758. The most prominent lineation is the trough at

306   the south flank of the seamount, which is a large graben that was probably formed during

307   the construction of the NER [*Sager et al., 2010*]. Other lineations have similar trends

308   crossing the top of the seamount, with several being traced across the entire summit (Fig.

309   9). Some seamount bathymetry contours have an angular nature, rather than being

310   rounded, and in several places have right angle bends and offsets similar to those seen at

14

311   sites 758 and 216. These offsets show no consistent trend, some being right-lateral and

312   others left-lateral.

313   Seismic lines show that the NER2 seamount is extensively faulted and the

314   bathymetric lineations are correlated with major faults (Figs. 9, 10). Compression is

315   clearly indicated by fault 4, which has a reversed geometry with the hanging wall

316   upthrust and bending of sedimentary layers (Fig. 10). Fault 3 is similar, but the reverse

317   geometry is not as clear. Other evidence of compression is the upwarp of sediment layers

318   observed between faults 1-2, 2-3, 8-9 and near fault 10. Faults 8-9 are associated with a

319   basement pop-up structure. Warping on the north side of fault 11 may also indicate

320   compression. This fault may also have a component of strike-slip motion as indicated by

321   the deformed trough and by slight differences in sediment character across the fault.

322   Fault 6 appears as a small, negative (extensional) flower structure, with two closely

323   spaced faults converging at depth. This fault may indicate strike-slip motion with a small

324   extensional component.

325   A number of active faults are rooted in offsets of acoustic basement (faults 4, 5, 7,

326   8, 9). For most of these, the basement offset is greater than that within the sediments or

327   at the surface, implying reactivation of a pre-existing basement fault.

328   **3.4 Site NER3 (7.7°S)**

329   Site NER3 covers much of a small, N-S-trending ridge segment (Fig. 11).

330   Although not as prominent as at other locations, bathymetric lineations are also observed

331   on the summit of the NER3 seamount. Most have nearly E-W trends, but there is

332   significant variability. These lineations correlate with active faults and summit basin

333   edges, implying that active deformation affects the seafloor topography. Unlike other

334   sites farther north, there are no apparent offset contours. NER3 acoustic basement is

335   highly dissected and offset, mostly from early extensional faults that formed rotated fault

336   blocks, probably formed during construction [*Sager et al., 2010*]. These faults strike

337   approximately E-W (Fig. 11) and appear to account for much of the broader topography

338   and the bathymetric lineations, which are formed by fault troughs or ridges.

339   Fault geometries imply that both compression and strike-slip faulting occur at this

340   site, with the former being dominant. Compression is indicated by reverse faults 14 and

341   15 (numbers in Fig. 12). Both faults show hanging walls upthrust relative to footwalls.

342   Fault 3 also appears to be reverse, with basement on the south side upthrust (Fig. 12).

343   Upwarped sediments indicate compression and are observed at faults 4, 10, 11, 14, 16,

344   and perhaps between 5-6 and 8-9. The folds at faults 11 and 14 are large enough to

345   create ridges imaged by the multibeam bathymetry. Compression is also indicated by the

346   basement pop-up feature at fault 14.

347   Strike-slip motion is suggested by subtle differences in sedimentary layer

348   thicknesses across a few faults. This situation occurs at faults 5, 6, 11, perhaps at 14, and

349   across faults 2-3 and 7-8 (Fig. 12). Faults 2-3 form a sag trough similar to features often

350   observed on strike-slip faults. Because fault 3 is a reverse fault, the combination of

351   interpreted compressive and strike-slip motions implies transpression across this set of

352   faults. Faults 7-8 form a graben that is reminiscent of the fault 2-3 trough. Although the

353   sense of motion is not obvious, the upwarp of sediment layers on the south side of this

354   pair likely indicates compression.

355   Seismic profiles show extensive early deformation of the NER3 ridge in the form

356   of offset and tilted fault blocks that appear normal in nature (Fig. 12B). Many of the

357   active faults connect to these basement offsets. In most cases, the offset of acoustic

358   basement is greater than that of overlying sediments (faults 1, 6, 10, 12-13, 15), implying

359   recent reactivation of an original basement fault. For fault 8, the offset of acoustic

360   basement is similar to that of upper sediment layers, suggesting that the entire basement

361   offset resulted from the active faulting. For fault 14, surface expression appears greater

362   than basement offset because of an expanded recent sediment section caused by recent

363   differential sedimentation.

364   **3.5 Site 214 (11.3°S)**

365   The Site 214 survey encompasses a broad area at the northern end of the high,

366   continuous ridge that makes up the southern NER. The surveyed portion of the ridge

367   summit contains three uplifts separated by two swales, both trending ~N70°E (Fig. 13),

368   that apparently formed from extension during formation of the NER [*Sager et al., 2010*].

369   Bathymetric lineations are few and no offset bathymetric contours are evident (Fig. 13).

370   Seismic sections in the Site 214 area show extensive faulting and most faults

371   appear to be normal faults as indicated by the hanging wall having moved downward

372   relative to the footwall (e.g., faults 7-11, 12-13, 17, 21, 22; numbers in Fig. 14).

373   Although the stress regime appears dominantly tensional, indications of possible

374   compression and strike-slip are observed. Sediment layer upwarp is noted between faults

375   2-3 and 4-6, implying compression. Sediment layers at faults 1 and 3 have a v-shape that

376   may indicate strike-slip motion. Thus, it appears that a regime of slight extension is

377   punctuated by zones of compression and strike-slip motion.

378   Acoustic basement is highly dissected at Site 214, with sediment infill indicating

379   that this intense normal faulting occurred at the time of or soon after ridge construction

380   [*Sager et al., 2010*]. Many of the active faults are rooted in these original faults. In

381   almost every case an increase in displacement with depth is consistent with basement

382   fault reactivation.

383   **3.6 Site 757 (17.1°S)**

384   Multibeam bathymetry data around Site 757 were collected by R/V *Sonne* [*Flueh*

385   *and Reichert, 1998; Grevemeyer et al., 2001*] and single channel seismic data come from

386   cruises RC2707 and ODP Leg 121. The bathymetry map (Fig. 15) shows that the site is

387   located atop the broad dome of a large seamount and there are few bathymetric contours

388   or features of interest. Small (<100 ms TWTT) offsets in the seafloor were mapped

389   (Figs. 15, 16) and are similar to those produced elsewhere by active faulting. Most faults

390   (e.g., numbers 1-3 in Fig. 16) appear to have normal fault geometry, with fallen footwalls

391   creating steep escarpments. Data quality is mediocre, with little detail imaged below the

392   seafloor, so fault interpretation is less certain than sites with recent data.

393   **3.7 Site 253 (25.5°S)**

394   The Site 253 survey is slightly offset from the DSDP drill site (Fig. 17) and

395   covers an area of the southern NER that is dissected by a large, NE-trending canyon.

396   Satellite-predicted bathymetry data [*Smith and Sandwell, 1997*] imply that the ridge is

397   rugged, with number of local highs and lows on the ridge top. Only a few tectonic

398   lineations are noted in the multibeam bathymetry data (Fig. 17), trending NE-SW

399   (~N70°E to N80°E).

400   Seismic data show that this part of the ridge also experienced extensive early

401   faulting during or shortly after construction, creating large offsets in the acoustic

402   basement as well as large grabens, most of which are filled by sediments (Fig. 18).

403   Seismic sections also show widespread active faulting. Most faults have small offsets

404   (<50 ms TWTT), but a few are larger, especially at the edges of large offset basement

405   fault blocks. Some cause small offsets and undulations of the seafloor (faults 1-9, 13, 17;

406   numbers in Fig. 18) and others are connected with small (fault 12) or large troughs (faults

407   14-15, 16, 18-20, 21, 22-23). Overall, the faults at Site 253 are mostly normal faults, but

408   there are some indications of other types of motion. Although inter-fault sediment

409   reflectors between faults 1-9 appear to be folded, an observation that could signify

410   compression, we interpret this geometry simply as coeval deformation and sedimentation

411   between closely-spaced normal faults within a zone of intense faulting (at mid-sediment

412   layer depths the faults are clearly normal and layer bending is insignificant). Fault 1

413   occurs at the edge of a small basement uplift that may have resulted from recent

414   compression because the sediment layer offset is approximately the same as the acoustic

415   basement offset.

416   Most active faults are connected to offsets in acoustic basement. For many, the

417   offset of basement or deep sediment layers is approximately the same as that in the upper

418   sediments, implying that the basement offset is a result of the recent faulting (faults 1, 5-

419   8, 13). Fault 17 shows less offset at seafloor than basement offset, whereas faults 21-23

420   have more seafloor topography than offset in deep layers. The former observation

421   implies that an original basement fault was reactivated whereas the latter observation

422   suggests that erosion may be a factor in creating these troughs. In some locations, the

19

423   sense of faulting may have changed. Faults 15 and 19 appear to be connected with

424   basement reverse faults, but the seafloor troughs (bounded by faults 14-15, 18-20)

425   indicate extension. These observations imply the reactivation of original basement faults

426   but with a different motion of the active faulting.

427   **3.8 Site 756 (27.3°S)**

428   No multibeam bathymetry data are available from Site 756. Satellite-predicted

429   bathymetry data [*Smith and Sandwell, 1997*] imply that the surface of the NER at this site

430   has significant topography (Figs. 15, 16) similar to nearby Site 253. Single-channel

431   seismic data from R/V *Robert Conrad* cruise RC2708 show numerous seafloor offsets

432   that are consistent with active faulting (Fig. 16). Although the geometries of most are

433   unclear, faults 4 and 5 (numbers in Fig. 16) appear to have normal geometry. Faults are

434   observed on most seismic lines, both N-S and E-W trending, implying that the fault

435   trends are SW-NE, similar to the bathymetric trends and fault trends at Site 253. Data

436   from Site 756 are of such low quality that little detail is seen below the seafloor, making

437   unique interpretations of fault nature difficult. Active faulting is indicated, but the sense

438   of most faults is uncertain.

439   **4. Discussion**

440   High-resolution multibeam bathymetry data and 2D multichannel seismic data

441   clearly show active faulting along the entire length of the NER. Although our data have

442   higher resolution than previous NER data sets, both the wide spacing of sites and the

443   coarse spacing of seismic lines at each survey site are limitations to the resolution of the

444   study. Within the survey sites, seismic lines are widely spaced, hampering definition of

445   fault geometry. Many faults have small offsets, are inadequately imaged, or have

446   ambiguous geometry, all of which also make some fault interpretations ambiguous.

447   Despite these cautions, the data are far better than any previously available and allow us

448   to make important observations about NER faulting.

449   **4.1 Reactivation of Original NER Faults**

450   Active faults visible at the seabed are usually connected with near-vertical steps in

451   the top of acoustic basement (the top of the NER volcanic pile). Analysis of differences

452   in the vertical separation of sediment layers relative to the throw on basement faults

453   indicates whether the recent faulting caused the basement fault or whether a pre-existing

454   fault was reactivated. In some instances the vertical offsets of the sedimentary and

455   basement faults are the same, implying that recent deformation caused the basement

456   offset. For many active faults the basement offset is greater than sediment offset,

457   implying that recent faulting reactivated an original basement fault. The reactivation of

458   pre-existing weaknesses by diffuse plate boundary faulting of the Indo-Australian plate is

459   not a new observation. The same occurs in the Central Indian Basin, where original

460   spreading-ridge-generated normal faults are reactivated as active thrust faults [*Bull and*

461   *Scrutton, 1992*]. Similarly, strike-slip faulting in the Wharton Basin is thought to occur

462   by the reactivation of original transform faults [*Deplus, 2001; Delescluse et al., 2012*].

463   Evidently the fracturing of the Indo-Australian plate is occurring by opportunistic

464   reactivation of weak zones in the lithosphere created by original faulting. Active fault

465   trends in both the NER and adjacent basins indicate that original fault azimuths, rather

466   than relative plate motion vectors (discussed in the next section) or other factors,

467   determine the pattern and direction of active faulting.

21

4.2 Deformation within the NER and Implications for Diffuse Plate Boundaries

468

469   It is expected that observed fault motion could be explained by relative plate motions

470   predicted by the three-plate model of *Royer and Gordon* [*1997*], but with uncertainty

471   about the locations of plate boundaries and the response of the lithosphere to the stress

472   field implied by the plate motions. This model is based primarily on seafloor spreading

473   rates and fracture zone trends along central Indian Ocean mid-ocean ridges, which define

474   the plate-pair Euler poles (Fig. 1) [*DeMets et al., 2010; Bull et al., 2010*]. These poles

475   predict significant variations in relative motions along the NER (Fig. 19A). Predicted

476   motion at a given location depends on the angle that the relative motion vector makes

477   with the plate boundary as well as the assumed plate geometry. Only the most likely

478   combinations are shown in Figure 19A, where it is assumed that the India - Australia and

479   Capricorn - Australia boundaries trend N-S, but the India - Capricorn boundary strikes E-

480   W. Figure 19 shows only the direction of relative motion, but not the magnitude. The

481   amount of movement between the plates is small but greatest for the India-Australia pair

482   (total ~125 km). This is slightly more than twice that for India-Capricorn and roughly

483   five times as much as for Capricorn-Australia [*Royer and Gordon, 1997*]. Both India-

484   Australia and India-Capricorn Euler poles lie well off the NER, consistent with greater

485   amounts of relative motion (Fig. 1) and greater seismicity (Fig. 2). The Capricorn -

486   Australia Euler pole is near the southern end of the NER and its 95% confidence ellipse

487   encompasses Sites 253 and 756, so the magnitude of relative motion is small and the

488   direction of motion is uncertain at these sites.

4.2.1 Northern NER (Sites 758 and 216)

489

490   In the northern NER, prominent WNW-ESE bathymetric lineations are observed at

491   both Sites 758 and 216 and correspond to major active faults that display evidence of

492   strike-slip motion, often with local compression and sometimes extension. Deformation is

493   mostly strike-slip at both sites, consistent with the observed dominance of strike-slip

494   focal mechanisms for northern NER earthquakes (Fig. 2). Compression also occurs at

495   both sites; although, it appears greater at Site 758. Thus, the overall picture in the

496   northern NER is of transpression. Signs of extension occur at both sites, but it is minor in

497   nature. Extension probably occurs on releasing bends where the fault trend deviates from

498   being parallel to the direction of relative motion across the fault, a common feature of

499   strike-slip faults.

500   Although all three Euler poles imply NW-SE compression in the northern NER, it is

501   probable that this location is part of the India-Australia plate boundary (Figs. 1, 19)

502   [*Royer and Gordon, 1997*]. The Euler pole for this plate boundary implies compression

503   at an angle ~45° from the trend of the NER (Fig. 19A, C). This direction is oblique to

504   both the WNW-ESE transform faults observed in the NER and to the ENE-WSW

505   trending fracture zones that are reactivated in the Wharton Basin [*Deplus, 2001;*

506   *Delescluse et al., 2012*]. Because the oblique compression is ~45° from the trends of the

507   fracture zones, it makes about the same angle with original spreading-ridge normal faults.

508   Both sets of faults are oriented approximately along Riedel shear directions (Fig. 19C),

509   which likely results in opportunistic reactivation of these faults. Back-projection of the

510   April 2012 Wharton Basin earthquake aftershock pattern suggests that the fault ruptures

511   are not exactly parallel to the local magnetic lineations [*Meng et al., 2012*]. It is unclear

512   whether the small deviation in direction is significant or whether rupturing cuts across the

513   Strike-slip faults with N-S orientations are not observed in the areas of the northern

514   NER that were mapped with multibeam bathymetry data. This finding suggests that prior

515   interpretations of N-S strike-slip motion within the NER [*Stein and Okal, 1978; Petroy*

516   *and Wiens, 1989*] are incorrect. Because all observed tectonic lineations in the northern

517   NER are oriented nearly WNW-ESE, it is likely that strike-slip earthquake focal

518   mechanisms in the northern NER indicate motion with that trend. Our data do not cover

519   seafloor in adjacent basins where reactivated, ENE-WSW-oriented fracture zones may

520   exist, so we cannot tell how the NER and Wharton Basin faults connect.

521   Strike-slip motion observed within the northern NER is distinct from N-S

522   compression in the Central Indian Basin and ENE-WSW strike-slip in Wharton Basin.

523   These differences imply that this part of NER is indeed a tectonic discontinuity as

524   indicated by *Delescluse and Chamot-Rooke* [*2007*]. Because the aftershock distribution

525   related to the April 2012 Wharton Basin earthquake implies a "lattice" of intersecting

526   WNW-ESE and ENE-WSW strike-slip faults located on the east side of the NER [*Meng*

527   *et al., 2012*], it is possible that observed NER faulting is the western edge of that fault

528   pattern.

529   **4.2.2 Central NER (Sites NER2, NER3)**

530   At Sites NER2 and NER3, in the middle of the predicted diffuse triple junction (Fig.

531   1), active faulting documented by the seismic reflection data is dominantly thrusting on

532   E-W trending faults. Unfortunately, no earthquake focal mechanisms have been

533   produced from this portion of the NER (Fig. 2), so such data cannot inform this

534   interpretation. The observation of E-W oriented thrust faults implies N-S compressive

535   stress, which could be a result of either India-Australia or India-Capricorn motion as both

536   vectors have appropriate orientations (Fig. 19A). Capricorn-Australia relative motion is

537   nearly parallel to the observed faults, but significant strike-slip motion is not supported

538   by fault observations. Because these two sites are adjacent to the India-Capricorn

539   deformation zone and have a similar style and direction, the observed Site NER2-NER3

540   faulting may linked to that in the Central Indian Basin deformation. However, India-

541   Australia relative motion is also plausible as a driver of faulting at this site. An important

542   difference from the Central Indian Basin is that thrust faults at NER2-NER3 have small

543   offsets, but those nearby in the Central Indian Basin can be much larger [*Bull and*

544   *Scrutton, 1992*], implying greater strain accumulation in the adjacent basin.

545   Evidence of strike-slip motion is observed on some faults within NER2-NER3,

546   suggesting that the relative motion at these sites includes a component parallel to the

547   faults. Strike-slip motion may occur because the relative motion vectors are not-quite

548   perpendicular to the E-W trend of spreading-ridge-formed precursor faults (Fig. 19C). If

549   true, this observation supports the idea that original fault sets localize deformation with

550   recent motions having components both parallel and perpendicular to the fault.

551   **4.2.3 Southern NER (Sites 214, 757, 253, and 756)**

552   In the northern and central NER, observed faulting is well-explained by the

553   predicted relative motions of the three plate system [*Royer and Gordon, 1997*]. In the

554   southern NER, the translation of relative plate motions into faulting is less clear. One

555   element of uncertainty is the significant shift in plate motions caused by the proximity of

25

556   the Capricorn-Australia pole to the southernmost NER and the fact that the NER crosses

557   from a region of extension to compression in the velocity field of the India-Australia

558   pole. The former situation means that the magnitude of relative motion changes rapidly

559   along the southern NER and the direction is highly uncertain. The latter causes relative

560   motion along a either N-S or E-W oriented faults to shift from convergence north of

561   ~11°S to extension farther south (Fig. 19A, compare Site NER2-NER3 to Site 214).

562   Faults observed in seismic sections at both Sites 214 and 253, at the north and south

563   ends of the high, linear section of the southern NER, mostly have a normal geometry.

564   Data from Sites 757 and 756 are of low quality and do not clearly show the geometry of

565   most observed faults. Although these data are consistent with observations at Sites 214

566   and 253, we base our interpretations on data from the two recently-surveyed sites.

567   Normal faulting is dominant at both sites, but displacement on active faults appears

568   small, indicating low strain. A few faults at each site show characteristics of possible

569   compression or strike-slip motion. The non-normal faults appear clustered, implying

570   zones of compression or strike-slip motion surrounded by normal faulting. This mixture

571   of fault types suggests that faulting in the southern NER is complex and possibly

572   incompletely defined by the small areas of seismic reflection data available.

573   Normal faulting is unexpected in the southern NER, given that the three focal

574   mechanisms located on this part of the ridge show thrust faulting and strike-slip

575   mechanisms occur in adjacent basins (Fig. 2). Relative plate motions for this part of the

576   NER should be described by the Capricorn-Australia Euler pole (Fig. 1). Although this

577   pole predicts extension for Site 756, it implies compression, not extension, from Site 253

578   northward (Fig. 19A). Both sites lie within the 95% confidence ellipse of the pole, so

26

579   relative motion predictions are uncertain for these sites. However, if the Euler pole is

580   actually located slightly farther north, then extension is expected at both sites (Fig. 19C),

581   which are then part of a zone of extension extending southwest from the southern NER

582   [*Royer and Gordon, 1997*] (Fig. 19B). Because of the proximity of the pole and its low

583   rotation rate [*Royer and Gordon, 1997*], relative motion between the two plates in this

584   area should be very small, but this is consistent with the low strain on observed faults.

585   According to Royer and Gordon [1997], Site 757 is located within the Capricorn-

586   Australia boundary whereas Site 214 is at the junction of that boundary with the diffuse

587   triple junction (Fig. 1). The Capricorn-Australia pole predicts convergence nearly

588   perpendicular to the NER at both locations. Although this prediction is consistent with

589   the thrust fault focal mechanism recorded near Site 757, it does not explain the

590   prevalence of normal faults in seismic sections. In contrast, the India-Australia pole

591   predicts extension at both sites (Fig. 19A), whether or not a fault is oriented N-S or E-W.

592   The abrupt shift from convergence at Site NER2-NER3 to extension at Site 214 could be

593   a result of the former being north of the India-Australia Euler pole and the latter being to

594   the south. For N-S trending faults, the change is small because the relative motion vector

595   has nearly the same orientation, but for E-W oriented faults, the shift is from nearly

596   perpendicular compression to extension.

597   Site 757 is located on a section of the NER that is too far south to be plausibly a part

598   of the India-Australia boundary. Because seismic data are unclear at this site, it is

599   possible that the observed active faulting is compression caused by Capricorn-Australia

600   motion, an interpretation consistent with the thrust focal mechanism located nearby (Fig.

601   2).

27

4.2.4. Tectonic Overview

602

603   We observe that active faulting within the NER is opportunistic, reactivating original

604   faults mostly in response to regional relative plate motions. It does not seem to matter

605   that the original fault fabric is often at a significant angle from the relative motion

606   vectors, the original faults are weak and therefore break before intact crust. Because the

607   regional stress pattern and relative plate motions are both usually oblique to the fault

608   fabric, many active faults appear to have complex motion.   In the northern NER, original

609   normal faults are reactivated mainly as strike-slip faults, but with a component of

610   compression (Fig. 19C, Sites 758, 216). In the central NER, a shift in relative motion

611   directions causes reactivation of early normal faults with mostly compressive motion, but

612   with a component of strike-slip (Fig. 19C, Sites NER2-NER3). The relationship of

613   broad-scale plate motions to active faulting in the southern NER is more complex.

614   Faulting appears a mixture, with widespread extension punctuated with compression or

615   strike-slip motion. This apparent paradox suggests that the southern NER has narrow

616   zones of deformation responding to the regional plate motions with surrounding areas of

617   slight extension. Extension at Sites 253 and 756 may be explained by inclusion in a zone

618   of Capricorn-Australia divergence south of the Euler pole for that plate pair (Fig. 19B).

619   Site 214 is interesting because it shows a dramatic shift from the compressional

620   deformation occurring only a few degrees of latitude farther north at Site NER2-NER3.

621   Given that fault motions at Sites NER2-NER3 and 214 can be explained by the India-

622   Australia pole, we favor the explanation that the NER north of ~11°S is part of the

623   boundary of that plate pair. This abrupt shift could instead represent a more complex

624   blending of deformation in the diffuse triple junction, but we have insufficient data to

28

625   support an explanation of greater complexity. Interestingly, the difference between Sites

626   NER-NER3 and 214 is also apparent in the active strain model of *Delescluse and*

627   *Chamot-Rooke* [2007], derived from earthquake focal mechanisms and geodetic GPS

628   measurements. This model shows strong, NNW-SSE compression in the central NER

629   from 3°-8°S, but only slight strain south of 8°S. The maximum strain axis direction near

630   Sites NER2-NER3 is coincident with India-Australia motion (Fig. 19A), suggesting this

631   portion of the NER is associated with that boundary.

632   No clear seismic data are available from the ~15° of the southern NER surrounding

633   Site 757. Although existing data show that faulting is occurring at that site, the type of

634   faulting is uncertain. Because earthquake focal mechanisms and the strain model

635   [*Delescluse and Chamot-Rooke, 2007*] indicate oblique compression approximately

636   coincident with expected Capricorn-Australia motion, it is likely that faulting in this zone

637   is mainly thrust faulting related to the convergence of these two plates.

638   It is clear from seismic data that changes in the style of faulting occur along the

639   NER, sometimes abruptly. Sites 216 and NER2 are separated by ~7° (~780 km) and the

640   mostly strike-slip style of faulting at Sites 758 and 216 is dramatically different from the

641   primarily thrust fault deformation at Sites NER2 and NER3. Between Sites NER3 and

642   214, separated by only ~2.5° (~260 km), there is an abrupt change from mainly thrust

643   faulting to mainly normal faulting. In addition, several sites (NER3, 214, 253) show

644   evidence of mixed faulting. These changes probably occur because the pre-existing fault

645   fabric at different locations responds to regional changes in relative plate motions and

646   stress orientations. Faulting sometimes appears to change more abruptly than expected

29

647   from the broad shifts in relative motion implied by the three-plate model, an indication

648   that pre-existing structure is an important factor in the fracturing of the plates.

649   Changes in fault style indicate that the NER crosses at least two different diffuse

650   boundaries. The northern NER (Sites 214, NER2-NER3, 216, and 758) appears to show

651   deformation related to the India-Australia plate boundary, whereas the southern NER

652   (Sites 757, 253, 756) shows Capricorn-Australia motion. It is also possible that the

653   diffuse triple junction is more complex and also shows India-Capricorn motion (i.e., Site

654   NER2-NER3). If the NER does not cross the India-Capricorn boundary, it cannot be far

655   away because the thrust faulting in this zone has been observed directly adjacent to the

656   northern NER (Fig. 19B; [*Weissel et al., 1980; Bull and Scrutton, 1992*]). Such an abrupt

657   change from one relative motion to another is consistent with the observed abrupt change

658   in earthquake style and with deformation models derived from earthquake motion

659   [*Deplus, 2001*; *Delescluse and Chamot-Rooke, 2007*].

660   **5. Conclusions**

661   Analyses of seismic reflection data shows that active faulting is found along the

662   entire ~4500 km length of the NER, but with variable intensity and style depending on

663   location relative to diffuse plate boundaries and relative plate motion Euler poles. At all

664   sites, recent deformation has reactivated spreading-center-formed normal faults.

665   Together with similar results in adjacent basins, this finding implies that Indo-Australian

666   plate fracturing occurs mainly by reactivation of faults formed at the time of lithosphere

667   creation. Fault directions are observed to correspond to the original structure rather than

668   the regional plate motion pattern, indicating that pre-existing structure is the most

669   important factor determining fault geometry.

30

670   In the northern NER (north of 1.5°N), the dominant deformation style is

671   transpression on faults having a WNW-ESE trend. The observed direction of strike-slip

672   motion is unexpected because prior interpretations of earthquake focal mechanisms

673   within the northern NER were interpreted to support N-S strike-slip, consistent with

674   reactivation of ancient fracture zones in the nearby Wharton Basin. Apparently NW-SE

675   compression within the India-Australia diffuse plate boundary reactivates original

676   spreading-center normal faults in the NER and fracture zones in the Wharton Basin along

677   oblique Riedel shear directions.

678   In the central NER (6.7°-7.7°S), deformation shifts to predominantly thrust faulting,

679   similar to that observed in the Central Indian Basin, perhaps with a minor amount of

680   strike-slip motion. Although this deformation could result from either India-Capricorn or

681   India-Australia relative motion, the latter is a simpler explanation because it agrees with

682   interpretations of sites to the north and south. A few faults show evidence of strike-slip

683   motion, suggesting that the stress pattern applied by regional plate motions has a

684   component parallel to the original faults.

685   Deformation style again changes abruptly between 7.7°S to 11.3°S. Southern NER

686   deformation is modest and is expressed mainly as normal faulting, but interrupted by

687   zones of strike-slip or compressional faulting. Extension at the southernmost end of the

688   NER is explained as part of a zone of Capricorn-Australia divergence south of that Euler

689   pole, whereas extension at 11.3°S is explained as part of the India-Australia boundary, as

690   are sites farther north. Although low-resolution seismic data in the gap between these

691   areas show active faulting, the style of faulting is unclear but likely to be Capricorn-

692   Australia convergence consistent with observed thrust fault focal mechanisms.

31

693   Seismic data from the NER indicate that diffuse deformation is widespread and often

694   complex, sometimes with mixtures of different fault types suggesting interplay of

695   regional stresses and pre-existing structures. Our interpretation is that the northern NER

696   shows India-Australia relative motion whereas the southern NER responds to Capricorn-

697   Australia motion. India-Capricorn deformation has been documented to the western edge

698   of the NER, implying that changes in deformation style can be abrupt. This observation

699   agrees with published findings that the northern NER is a break between deformation

700   fields on either side. Although observed deformation can be understood by the

701   framework of larger plate motions, faulting is more complex than existing plate models

702   predict.

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824 **Figure Captions**

825 Figure 1. Ninetyeast Ridge environs and tectonic setting. Background plot is satellite-

826 predicted bathymetry [*Smith and Sandwell, 1997*]. Shaded areas around the NER

827 represent diffuse plate boundaries (I-C=India-Capricorn, C-A=Capricorn-Australia, I-

828 A=India-Australia; DTJ=diffuse triple junction) [*Royer and Gordon, 1997*]. Stippled

829 zone northwest of the NER indicates the area of lithospheric compression resulting from

830 India-Capricorn convergence [*Krishna et al., 2001; 2009*]. Red boxes show study sites.

831 Red-filled circles denote Euler poles: IN-CP =India-Capricorn, IN-AU=India-Australia,

832 CP-AU=Capricorn-Australia [*DeMets et al., 2010*]. Red ellipses show pole 95%

833 confidence regions. Red filled square is updated IN-CP pole from *Bull et al.* [*2010*].

834 ASP=Amsterdam-St. Paul Plateau; BR=Broken Ridge; CR=Carlsberg Ridge;

835 CLR=Chagos-Laccadive Ridge; JT=Java Trench; SEIR=Southeast Indian Ridge.

836 Figure 2. Earthquakes in the Ninetyeast Ridge vicinity. Left panel shows epicenters from

837 1970-2012 with symbols scaled with body-wave magnitude (scale at bottom). Right

838 panel shows focal mechanisms for the same period. Background is satellite-predicted

839 bathymetry [*Smith and Sandwell, 1997*]. Data source: *International Seismological*

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841 Figure 3. Shaded relief bathymetry and tectonic interpretation maps of the Site 758

842 survey. High detail area is covered with multibeam echosounder data, whereas low-

843 resolution data are satellite predicted depths [*Smith and Sandwell, 1997*]. (left)

844 Bathymetry. Thin black lines are seismic lines. Open circle shows location of ODP Site

845 758. Bathymetry contours are at 200-m intervals and contour labels are in km. (right)

846 Tectonic interpretation. Red dashed lines show bathymetric lineaments. Blue lines

847   highlight contours with sharp bends. Faults observed in seismic profiles are marked by

848   symbols along seismic track lines; gray symbols denote less certain interpretations.

849   Circled letters identify seismic lines in Figure 4 whereas white track segments denote the

850   extent of the seismic profiles shown in that figure.

851   Figure 4. Seismic line examples showing active faults from the Site 758 survey. Seismic

852   sections plot two-way travel time versus distance. Arrows mark faults. Gray arrows

853   denote probable, but less certain fault interpretations. Locations of seismic sections are

854   shown in Figure 3 (letters A, B, C denote line segments labeled in that figure). Numbers

855   identify faults mentioned in the text.

856   Figure 5. Fault interpretation map for single-channel seismic data from cruise RC2705

857   near ODP Site 758.   Fault symbols are plotted on seismic lines. High-resolution

858   bathymetry covers the area shown in Figure 3. White line shows the location of the

859   seismic line shown in Figure 6. Low-resolution bathymetry contours are from satellite

860   predicted bathymetry [*Smith and Sandwell, 1997*].

861   Figure 6. Single channel seismic profile from R/V *Robert Conrad* cruise RC2705.
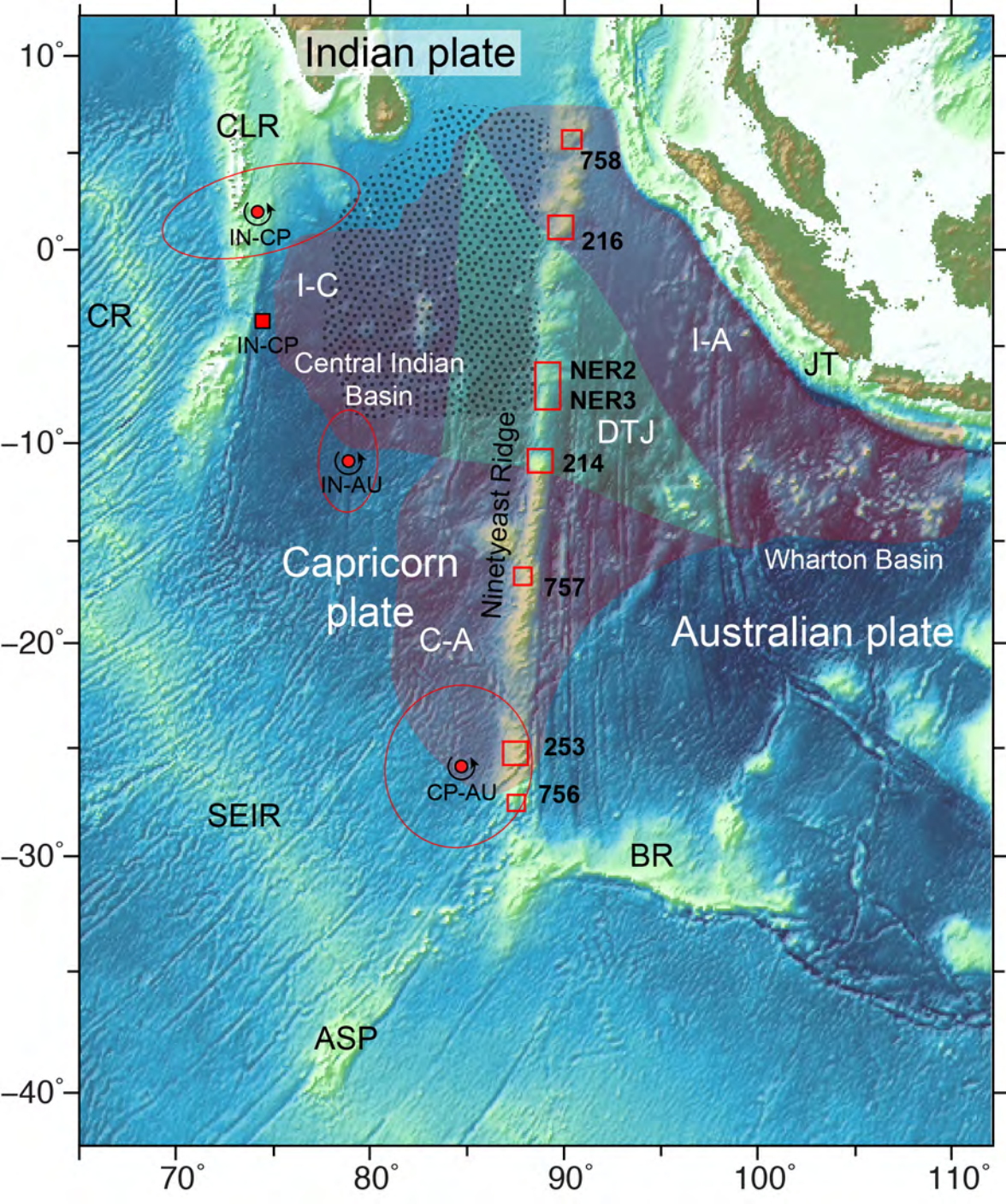
862   Conventions as in Figure 4.

863   Figure 7. Shaded relief bathymetry map (left) and tectonic interpretation (right) of the

864   Site 216 survey. White lines denote seismic profiles shown in Figure 8. Open circle

865   shows location of ODP Site 216. Blue stars show locations of aftershock epicenters

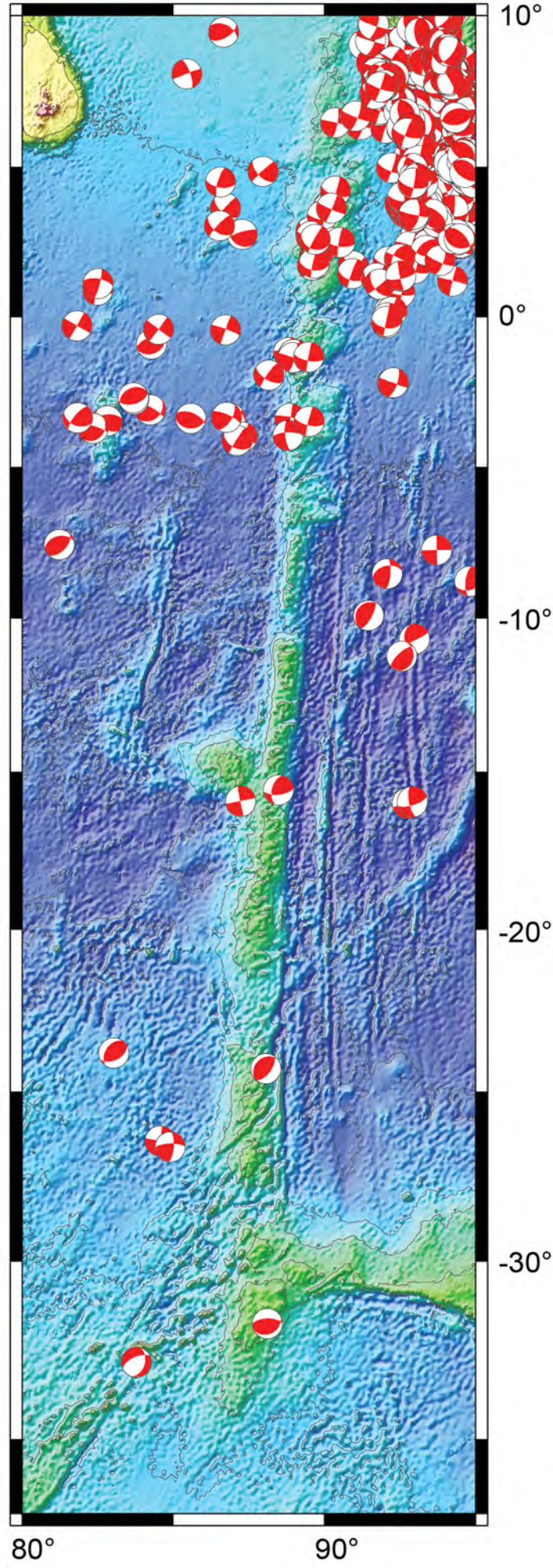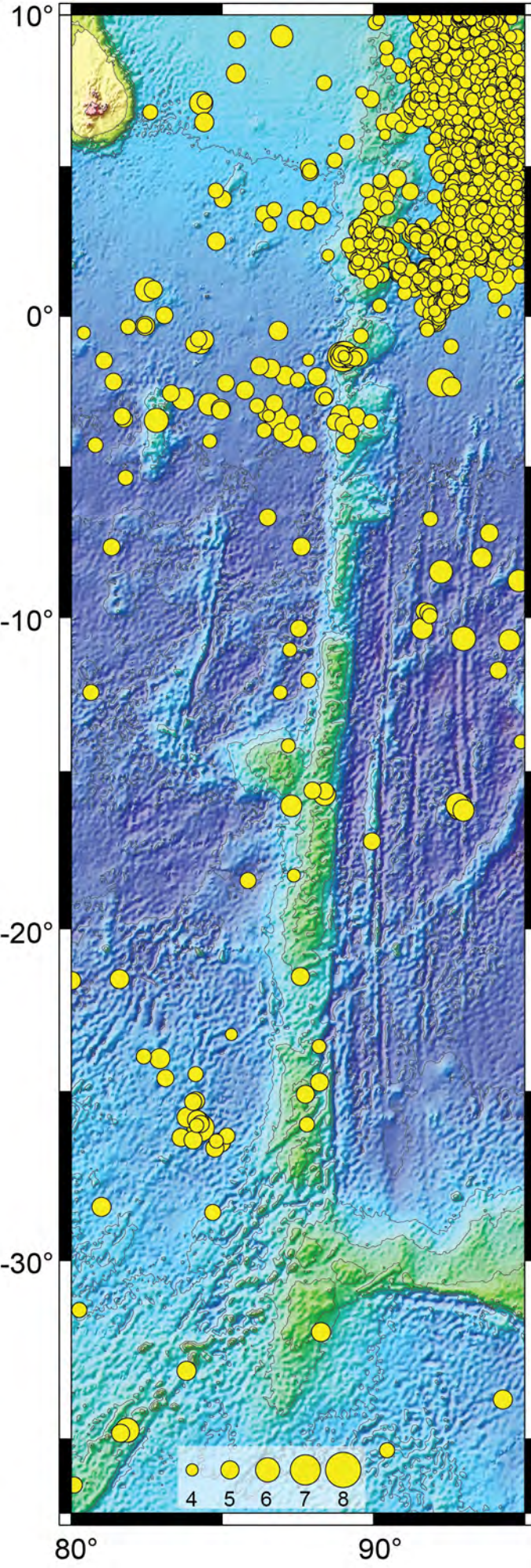866   associated with the 11 April 2012 Wharton Basin earthquake.

867 Figure 8. Seismic line examples showing active faults from the Site 216 survey.

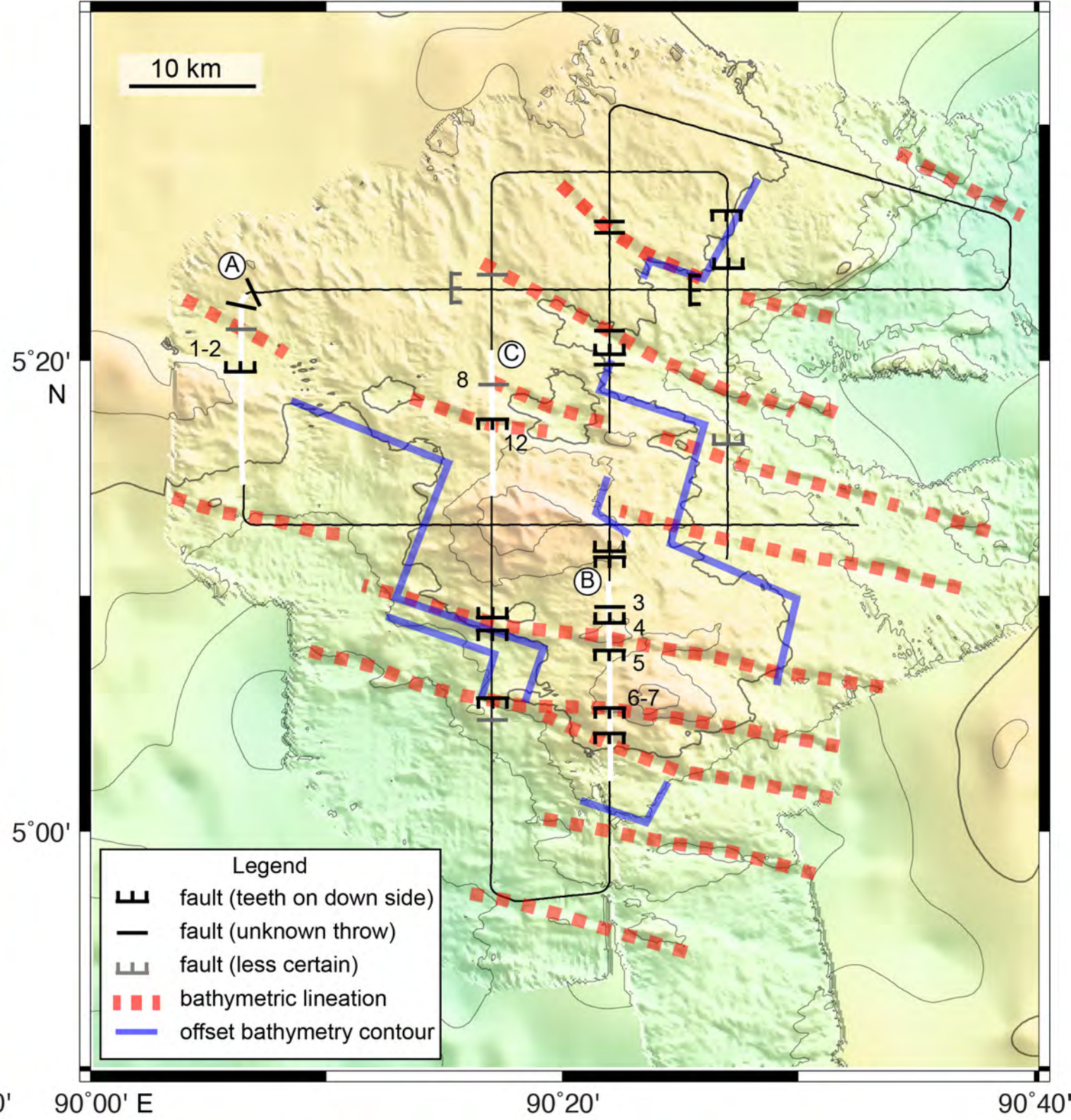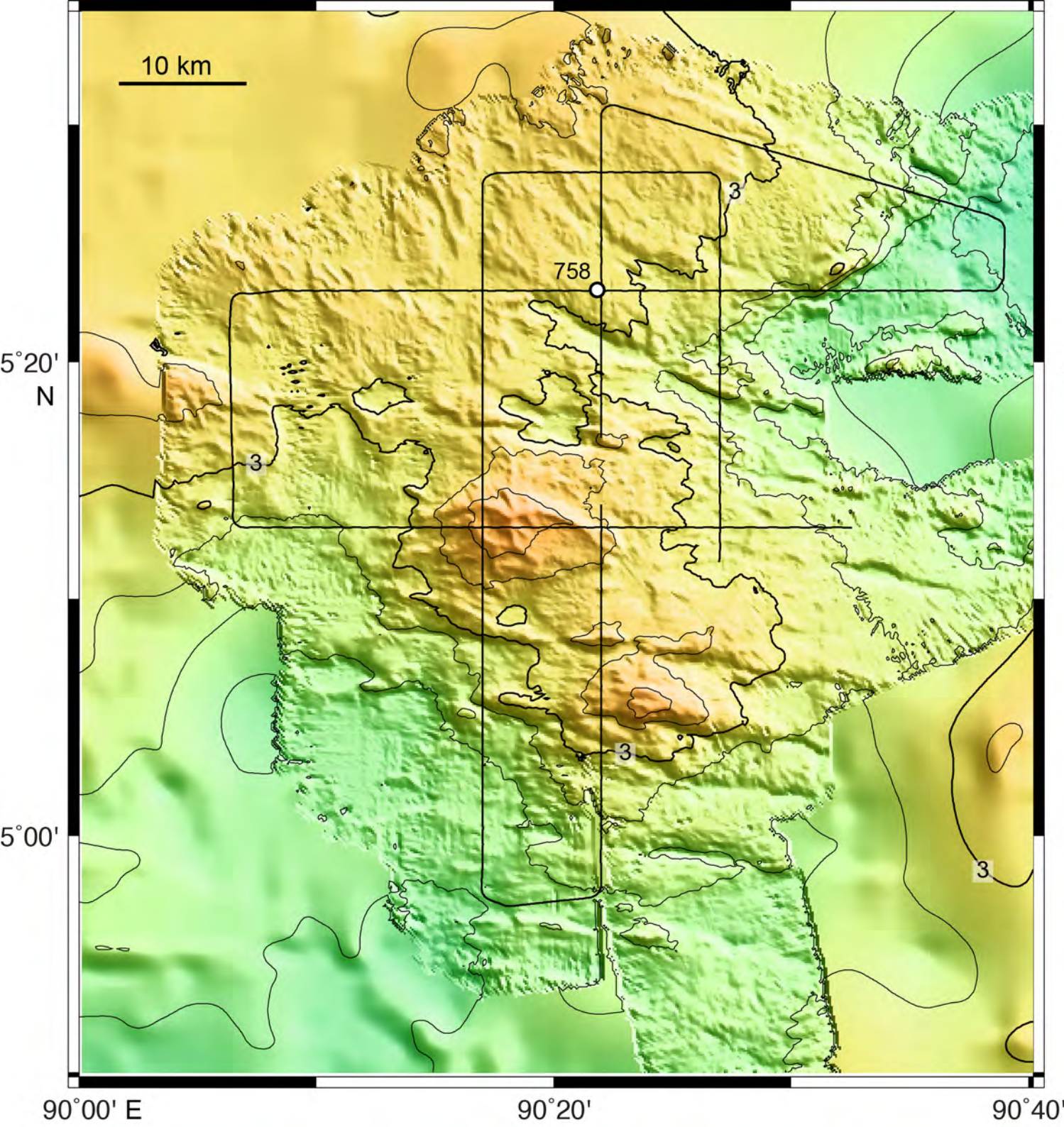868 Conventions as in Figure 4. Locations of seismic sections shown in Figure 7.

869 Figure 9. Shaded relief bathymetry map (left) and tectonic interpretation (right) of the

870 Site NER2 survey area. White lines denote seismic profiles shown in Figure 10.

871 Figure 10. Seismic line examples showing active faults from the Site NER2 survey.

872 Conventions as in Figure 4. Locations of seismic sections shown in Figure 9.

873 Figure 11. Shaded relief bathymetry map (left) and tectonic interpretation (right) of the

874 Site NER3 survey. White lines denote seismic profiles shown in Figure 12.

875 Figure 12. Seismic line examples showing active faults from the Site NER3 survey.

876 Conventions as in Figure 4. Locations of seismic sections shown in Figure 11.

877 Figure 13. Shaded relief bathymetry map (left) and tectonic interpretation (right) of the

878 Site 214 survey. White lines denote seismic profiles shown in Figure 14. Open circle

879 shows location of Site 214.

880 Figure 14. Seismic line examples showing active faults from the Site 214 survey.

881 Conventions as in Figure 4. Locations of seismic sections shown in Figure 13.

882 Figure 15. Shaded relief bathymetry around Site 757 (left) and Site 756 (right) and fault

883 interpretations from single-channel seismic data. Heavy line shows ship track of cruises

884 RC2708 (left) and RC2707 (right). Site 757 bathymetry data are multibeam data from

885 R/V *Sonne* [*Flueh and Richert, 1998*]. Dashed line in Site 757 survey shows ship track

886 for seismic data collected by the D/V *JOIDES Resolution* during ODP Leg 121

887 [*Shipboard Scientific Party, 1989a; 1989b*]. Site 756 bathymetry is predicted from

888   satellite gravity [*Smith and Sandwell, 1997*]. Interpreted fault symbols are as in other

889   figures (see Figure 3). White portions ship tracks are profiles shown in Figure 16.

890   Figure 16. Single channel seismic profiles from R/V *Robert Conrad* cruises RC2707 and

891   RC2708. Conventions as in Figure 4.

892   Figure 17. Shaded relief bathymetry (left) and tectonic interpretation (right) maps of the

893   Site 253 survey. White lines show seismic profiles shown in Figure 18. Open circle

894   shows location of Site 253.

895   Figure 18. Seismic line examples showing active faults from the Site 253 survey.

896   Conventions as in Figure 4. Locations of seismic sections shown in Figure 17.

897   Figure 19. Tectonic sketch of relative plate motions, plate boundaries, and inferred fault

898   motions for the Ninetyeast Ridge. (A) Relative plate motions calculated from plate pair

899   Euler poles [*DeMets et al., 2010*]. Arrows show azimuth and sense of motion. Inward

900   pointing arrows denote compression whereas outward-pointing arrows indicate extension.

901   Black arrows show Capricorn-Australia motion (C-A), middle gray arrows represent

902   India-Australia motion (I-A), and light gray arrows show India-Capricorn motion (I-C).

903   To infer extension and convergence, the plates are assumed to have the configuration

904   shown in Figure 1 with the India-Australia and Capricorn-Australia boundaries oriented

905   N-S but the India-Capricorn boundary trending E-W. In the northernmost NER,

906   Capricorn-Australia motion is not shown because this is an unlikely pairing in this area.

907   The same is true for India-Australia at the southernmost sites. (B) Sketch of plate

908   boundaries around the NER. The large dot pattern shows the zone of India-Capricorn

909   compression [*Krishna et al., 2001; 2009*], the stippled area denotes the India-Australia

910   boundary, and large and small dot patterns indicates the Capricorn-Australia boundary

911   with the latter being a zone of extension and the former, a zone of compression [*Royer*

912   *and Gordon, 1997*]. Arrows indicate relative motions predicted by the three plate model.

913   (C) Fault interpretations at survey sites. Boxed diagrams illustrate relative plate motions

914   at the study sites and the fault response. Numbers are site identifiers. The horizontal

915   dashed line represents an E-W fault. Heavy arrows indicate plate motions predicted by

916   three-plate model (IN=India, CP=Capricorn, AU=Australia; *Royer and Gordon* [*1997*]).

917   Small arrows indicate motions along the faults; dark arrows denote the sense of primary

918   motion and gray arrows represent secondary sense of motion. Elliptical diagram for Sites

919   758-216 shows Riedel shears appropriate for that area.

920

Legend

⊢ ⊣	fault (teeth on down side)
——	fault (unknown throw)
⊢ ⊣	fault (less certain)
▪▪▪▪	bathymetric lineation
——	offset bathymetry contour

Site 758 Line 1A

Site 758 Line 4

Site 758 Line 6

Legend

Symbol	Description
⊢⊣ E	fault (teeth on down side)
—	fault (unknown throw)
—	fault (less certain)
◇	fault with extension
✳	fault with compression
▪▪▪	bathymetric lineation
▬▬	offset bathymetry contour

A) Site 216 Line 1

B) Site 216 Line 8

C) Site 216 Line 10

Legend

- ⊢E ⊢E fault (teeth on down side)
- — | fault (unknown throw)
- | | fault (less certain)
- ◆ fault with extension
- ✳ fault with compression
- ▪▪▪ bathymetric lineation
- ▬▬ offset bathymetry contour

A — Site NER2 Line 7

N / S

two-way traveltime (sec)

2 km

1 2 3 4

B — Site NER2 Line 11

N / S

two-way traveltime (sec)

2 km

5 6 7 8 9 10

C — Site NER2 Line 13

N / S

two-way traveltime (sec)

2 km

11

Legend

⊢ ⊣	fault (teeth on down side)
——	fault (unknown throw)
⊢ ⊣	fault (less certain)
◈	fault with extension
✳	fault with compression
▨	faulted zone
▰▰	bathymetric lineation

A) N — Site NER3 Line 1a — S
two-way traveltime (sec)
1 2 3 4 5 6
2 km

B) N — Site NER3 Line 1b — S
two-way traveltime (sec)
2 km
7 8 9 10 11

C) N — Site NER3 Line 6 — S
two-way traveltime (sec)
12 13 14 15 16
2 km

(A) N — Site 214 Line 1a — S
2 km
1 2 3
two-way traveltime (sec)
2.5
3.0

(B) N — Site 214 Line 1b — S
2 km
4 5 6 7 8 9 10 11 12 13 14
two-way traveltime (sec)
2.5
3.0

(C) N — Site 214 Line 5 — S
2 km
15 16 17 18 19 20 21 22
two-way traveltime (sec)
2.5
3.0
3.5

Site 757

E   RC2707 15 August 1986   W N   S W   Lines 3, 4, 5   E

CC   1   2   CC   CC   3   5 km

time (UTC) 2230   0000   0030   0100   0130   0200

two-way traveltime (sec)
2.0
2.5
3.0

Site 756

N   RC2708 20 September 1986   line 7   S

5 km

4   5

two-way traveltime (sec)
1.5
2.0
2.5
3.0

time (GMT) 1100   1130   1200   1230   Time (UT)

A. Site 253 Line 1a

B. Site 253 Line 1b

C. Site 253 Line 9