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1 **Cenozoic contourites in the eastern Great Australian Bight, offshore southern**
2 **Australia: implications for the onset of the Leeuwin Current**

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12
13 **ABSTRACT**

14
15 Thermohaline oceanic currents influence global heat transfer, controlling local and global
16 variations in climate, biodiversity, and the terrestrial biosphere. Paleooceanographic studies
17 typically use biostratigraphic and geochemical proxies to reconstruct the dynamics of these
18 currents in Earth's ancient oceans, although seismic reflection data have also been
19 successfully employed, most commonly in the North Atlantic Ocean. Here we use 2D seismic
20 reflection data from the Ceduna Sub-basin, Great Australian Bight, offshore southern
21 Australia to describe middle Eocene-to-Recent contourites deposited within an overall
22 carbonate-dominated succession. These deposits comprise large (100 m wavelength by up to
23 50 m tall) bedforms and deep (10–90 m), wide (up to 3 km) erosional scours. The scours are
24 particularly well-developed at one specific stratigraphic level, defining moats that encircle
25 Middle Eocene shield volcanoes, which formed syn-depositional bathymetric highs. We
26 suggest that sediment erosion, transport, and deposition record middle Eocene initiation of
27 the Leeuwin Current, one of the most important ocean currents in the southern hemisphere.
28 Deepest seabed scouring occurs within the middle of the middle Eocene-to-Recent sequence,
29 and may reflect middle Miocene waxing of the so-called 'proto-Leeuwin Current', possibly
30 driven by changes in ocean circulation patterns caused by the Miocene Global Optimum. The
31 results of this seismic reflection-based study are consistent with results derived from other
32 paleooceanographic proxies, thereby highlighting the continued key role seismic reflection
33 data have in understanding the occurrence, geographical distribution, and significance of
34 ancient ocean currents.

35

36 **Introduction.** By influencing seawater temperature and salinity, ocean current activity
37 controls regional and global trends in climate and biodiversity. Determining past changes in
38 thermohaline circulation patterns in the world's oceans is thus important to understanding
39 how climate and biodiversity varied in deep time and, therefore, may change in the future (cf.
40 "geological analogues" of IPCC, 2007; see also e.g., Henderson, 2002; Wunsch, 2002;
41 Rahmstorf, 2003; Wyrwoll et al., 2009). Paleoceanographic analysis commonly relies on
42 biostratigraphic and geochemical proxy data, which: (i) are expensive to collect, and typically
43 only collected on academic scientific cruises (e.g. IODP); (ii) are spatially limited (i.e.
44 collected over a relatively small area within a discrete stratigraphic intervals); and (iii) do not
45 typically provide a physical (i.e. stratigraphic) record of the initiation, extent, and decay of
46 oceanographic currents (e.g. von Blackenburg, 1999; Henderson, 2002). Seismic reflection
47 data can image very large (up to 10's of metre thick, and several hundred-to-tens of
48 kilometres long) contourite systems, which provide an explicit record of ocean current-
49 driven, erosion and reworking of the ancient seabed (e.g. Boldreel et al., 1998; Davies et al.,
50 2001; Faugères et al., 1999; Rebesco and Stow, 2001; Stow et al., 2003; Due et al., 2006;
51 Hohbein et al., 2012; Rebesco et al., 2014). When integrated with more widely used
52 paleoceanographic proxies, as they have been most commonly and successfully in the North
53 Atlantic Ocean (e.g. Tucholke, 1979; Tucholke & Mountain, 1979; Mountain & Miller, 1992;
54 Davies et al., 2001; Müller-Michaelis et al., 2013; Calvin Campbell & Mosher, 2016; Boyle
55 et al., 2017), seismic reflection data form a key part of the oceanographer's toolkit.

56 In this study we use 2D seismic reflection data from the Ceduna Sub-basin, Great
57 Australian Bight, offshore southern Australia to identify and map middle Eocene-to-Recent
58 contourites, which possibly record the middle Eocene initiation of the current now known as
59 the Leeuwin Current. Although its age of initiation is debated, the present Leeuwin Current is
60 the longest (5000 km) and one of the most important ocean currents in the southern
61 hemisphere (Fig. 1A). It is connected to and samples the global thermohaline system via the
62 Indonesian Gateway (Feng et al., 2009), flowing southwards at relatively shallow depths
63 (<300 m) and modest speeds (<2 m s⁻¹, but as low as 0.3–0.5 m s⁻¹ in the Great Australian
64 Bight) along the western coast of Australia and thereafter eastwards into the Great Australian
65 Bight (Fig. 1A) (Cresswell and Golding, 1980; Cresswell & Domingues, 2009). Transporting
66 warm, low-salinity waters derived from the South Equatorial Current within a relatively
67 narrow band (<100 km), the Leeuwin Current contributes to climatic variations and
68 vegetation patterns (e.g., Caputi, 2001; Feng et al., 2009; Wyrwoll et al., 2009), and

69 continent-scale biodiversity patterns by transporting otherwise low-latitude fauna to
70 anomalously high latitudes (e.g., Cann and Clarke, 1993; McGowran et al., 1997; Passlow et
71 al., 1997). By providing what we think is the first physical evidence for ocean current activity
72 in relatively deepwater, offshore southern Australia, our seismic reflection-based study
73 broadly supports studies proposing a middle Eocene initiation age for the Leeuwin Current
74 (McGowran et al., 1997; see also Feary and James, 1995, 1998). More generically, our study
75 confirms that seismic reflection data, if integrated with biostratigraphic and geochemical
76 proxies, can help improve our understanding of deep-time dynamics of the Earth's ancient
77 oceans.

78

79 **Geological Setting.** The Ceduna Sub-basin is located in the Bight Basin, offshore southern
80 Australia (Fig. 1A), and formed in response to Jurassic-to-Early Cretaceous rifting and Early
81 Cretaceous-to-Recent, post-rift thermal subsidence. Numerous submarine volcanoes were
82 emplaced during earliest Middle Eocene magmatism at *ca.* 42 Ma (the 'Bight Basin Igneous
83 Complex'; Schofield & Totterdell, 2008; Jackson, 2012; Magee et al., 2013), with the
84 volcanoes overlapped by the fully marine, middle Eocene-to-Recent, carbonate-dominated
85 Nullarbor Limestone (Fig. 1B) (Schofield & Totterdell, 2008). Schofield & Totterdell (2008)
86 and Jackson (2012) identify numerous scours in the Nullarbor Limestone, although they do
87 not explore their age or origin, their genetic relationship to the middle Eocene volcanoes, or
88 the potential paleoceanographic significance of their causal current. There are no direct
89 constraints on middle Eocene-to-Recent water depths in the distal Ceduna Sub-basin,
90 although the heights of Eocene clinoforms along the northern basin margin (Feary and James,
91 1995, 1998; McGowran et al., 1997) and the preservation of pristine submarine volcanoes
92 within fully marine sediments (Magee et al., 2013; Jackson (2012) suggests the basin
93 deepened to a few hundred metres (i.e. broadly comparable to the present depth of the
94 Leeuwin Current; see above) during middle Eocene flooding (see also McGowran et al.,
95 1997; Shafik, 1983; 1990). The Ceduna Sub-basin lies outboard of the modern day shelf edge
96 in water depths of 200–4000 m; the seabed in the study area is below the influence of the
97 modern Leeuwin Current, which extends to depths of *c.* 300 m (Feng et al., 2009).

98

99 **Paleoceanography of the Great Australian Bight.** The Quaternary extent and dynamics of
100 the Leeuwin Current in the Great Australian Bight are relatively well understood (Cresswell
101 and Golding, 1980; Feng et al., 2009; Wyrwoll et al., 2009), whereas its timing of initiation,
102 and its pre-Quaternary eastward 'reach' into the Great Australian Bight, remain uncertain.

103 Based on their discovery of warm-water, Eocene microfauna in the Otway Basin, McGowran
104 et al. (1997) suggested an even older, middle Eocene age of initiation for the Leeuwin
105 Current in the Great Australian Bight, arguing these fauna were likely derived from warm
106 low-latitudes (i.e. via the proto-Leeuwin Current) and not cold high-latitudes (i.e. via the
107 Flinders Current) (Fig. 1A); this interpretation is supported by fully coupled climate model
108 simulations (Huber et al., 2004). However, pre-Early Oligocene initiation of the Leeuwin
109 Current is disputed given that opening of the Tasmanian Gateway, which facilitated
110 eastwards flow of warm ocean waters along southern Australia into the Pacific, did not occur
111 until the Early Oligocene (e.g. Stickley et al., 2004; Wyrwoll et al., 2009). These studies
112 together suggest the proto-Leeuwin Current in some way shaped the Eocene-to-Recent
113 stratigraphic evolution of the Great Australian Bight shelfal regions, although the
114 stratigraphic expression of time-equivalent, basin-centre units, which should also record the
115 initiation and influence of this important ocean current, has yet to be documented.

116 Although middle Eocene initiation of the Leeuwin Current is disputed, there is
117 evidence from IODP Leg 182 that anomalously warm waters entered the Great Australian
118 Bight during at least the middle Miocene, possibly in response changes in ocean circulation
119 driven by the Miocene Climatic Optimum (e.g. Savin et al., 1975; Feary and James, 1995,
120 1998; Gourley and Gallagher, 2004). For example, McGowran et al. (1997) document the
121 ‘Little Barrier Reef’, a thick (350 m), laterally extensive (>475 km long), rimmed carbonate
122 platform developed along the northern margin of the Bight Basin (Fig. 1A).

123

124 **Data and methods.** Our dataset consists of 109 time-migrated, zero-phase, 2D seismic
125 reflection lines that have a cumulative line length of *c.* 13,000 km and cover *c.* 44,000 km²
126 of the central Ceduna Sub-basin (Fig. 1A). The NW- and NE-trending lines are spaced 4–16 km
127 and 4–8 km, respectively (Fig. 2).

128 Biostratigraphic data from the Potoroo-1 borehole, which is located *c.* 200 km NW of
129 the main study area, directly constrain: (i) the age of a key, regionally mappable seismic
130 horizon defining the top of the Cretaceous (Horizon A); and (ii) the presence of Eocene,
131 Oligocene, and Miocene rocks in the post-Cretaceous stratigraphy in the northern Ceduna
132 Sub-basin (Fig. 2; DR1). A regional 2D seismic profile passing through Potoroo-1 allows us
133 to map the very distinct top Cretaceous reflection into our study area, although overlying,
134 lower-amplitude reflections near the top of the Eocene and Oligocene successions (Fig. 3) are
135 harder to correlate over such a long distance (i.e. *c.* 300 km) (DR3). However,
136 biostratigraphic data from Potoroo-1 and regional seismic data together provide strong

137 evidence that strata *directly* overlying Cretaceous strata within the study area are almost
138 undoubtedly pre-Quaternary (i.e. older than previous estimates of the onset of Leeuwin
139 Current activity), and more likely Paleocene to Eocene.

140 Based on seismic-stratigraphic relationships (e.g. onlap, downlap, erosional
141 truncations, changes in seismic facies) we map four key seismic reflections within the study
142 area; the lowermost horizon, A, correlates with the top Cretaceous horizon identified at the
143 location of Potoroo-1, whereas Horizon C defines the top of the middle Eocene volcanoes
144 (Horizons A–D; Figs 1B, 2 and 3). Well-log data from Potoroo-1 and Gnarlyknots-1a
145 indicate the relatively thin (<300 m) Nullarbor Limestone has a fairly constant P-wave
146 velocity of 2100 m s⁻¹ (cf. Espurt et al., 2009); this allows us to convert measurements in
147 milliseconds two-way time (ms TWT) to metres (e.g. 100 ms TWT=105 m). Extrusive
148 igneous bodies were identified and mapped using the geometric and geophysical criteria
149 outlined by Totterdell & Schofield (2008), Jackson (2012) and Magee et al. (2013). Our 2D
150 seismic lines are widely spaced relative to the size of the intra-Nullarbor features we describe
151 below, meaning we cannot document their full, three-dimensional external form or internal
152 architecture (cf. Calvin Campbell & Mosher, 2016). However, intra-Nullarbor scours and
153 ‘mounded’ seismic facies are typically imaged on and can be mapped between, several
154 adjacent seismic lines. In particular, it is clear that the scours are only developed adjacent to
155 and define ‘moats’ that encircle the volcanic vents (Figs 2 and 4).

156

157 **Description of intra-Nullarbor seismic facies.** We define two main stratal units within the
158 Nullarbor Formation (SU1-2), separated by a major erosional surface (Horizon D; Figs 1B
159 and 4). The base of SU1 is defined by a high-amplitude, laterally-continuous, positive
160 seismic reflection defining the contact between the Pidinga Formation and the Nullarbor
161 Limestone (i.e. Horizon B), or a series of volcanoes (i.e. Horizon C) (Figs 1B and 4). SU1
162 comprises the lower part of the Nullarbor Limestone and, away from the volcanoes, is
163 typically characterised by low-to-moderate amplitude, parallel-to-sub-parallel, very
164 continuous reflections (Fig. 4). Closer to the volcanoes (i.e. <2 km), a series of gently-
165 dipping (<4°) reflections are developed in SU1, and these locally display bilateral downlap
166 onto the underlying reflections and thus define convex-up, ‘mounded’ bodies (Figs 4B–D).
167 These inclined reflections, which either dip towards (Fig. 4A) or away (Figs 4C–D) from the
168 volcanoes, typically overlie low-angle (<6°) erosional surfaces, which are up to 2 km wide
169 and display up to 100 m of relief; these surfaces pass laterally into (seismically) conformable
170 surfaces (Fig. 4).

171 The base of SU2 is locally defined by a major erosion surface along which numerous
172 scours are developed (Horizon D; Figs 1–4). These scours locally define a series of ‘moat-
173 like’ features that fully or partly encircle 15 of the 57 vents present in the Ceduna Sub-basin
174 (e.g. Fig. 2). The scours have a relief of 10–90 m, extend <3 km from the volcanoes, and their
175 flanks dip 0.1–6.1°, being best-developed around volcanoes that are typically >200 m tall.
176 Some of the scours are asymmetric, consisting of a long, gently dipping outer margin inclined
177 towards the vents and a shorter, more steeply-dipping surface that dips away from the vents
178 (Figs 4B–D). However, our 2D seismic data do not allow us to confidently determine if the
179 scours are consistently asymmetric in one direction, or if they are preferentially developed on
180 one side of the vents (Fig. 2). Two main types of seismic facies fill the scours: (i) high-
181 amplitude, ‘mounded’ reflections, which have a relief of up to 50 m and a distance of 100–
182 200 m between adjacent mound crests (Fig. 4B); and (ii) low-to-high amplitude, gently-
183 dipping (<2°), moderately discontinuous to laterally-continuous reflections (Fig. 3). The
184 upper part of SU2 is dominated by low-to-high amplitude, flat-lying to gently-dipping (<2°),
185 laterally-continuous reflections (Fig. 4), with erosionally based packages of chaotic
186 reflections being locally developed.

187

188 **Interpretation of intra-Nullarbor features.** Based on their development in a fully marine
189 succession and given that post-Middle Eocene water depths were probably at least several
190 hundred metres (see Jackson, 2012), it is unlikely the intra-Nullarbor scours and mounds
191 formed subaerially. Furthermore, the coeval basin margin, which was likely located several
192 hundred kilometres to the north, was carbonate-dominated and constructional (Fig. 1; see also
193 Feary and James, 1995, 1998), suggesting only limited sediment bypass to deep-water, and
194 that voluminous, strongly erosional gravity currents, such as turbidity currents, were likely
195 not responsible for the formation of the intra-Nullarbor scours and mounds. Although large
196 mounded bodies, typically interpreted as sediment waves, are commonly observed in many
197 deepwater depositional systems, scours of the irregular shape and size to those observed here
198 are not (e.g. Posamentier & Kolla, 2003).

199 Based on their development in a fully marine succession deposited in several
200 hundreds of metres of water, our preferred interpretation is that the scours formed in response
201 to ocean current-related incision of the seabed (Fig. 5). Such scours are common in modern
202 seas and oceans, typically in association with channel-related contourite drifts (*sensu* Stow et
203 al., 2002). The spatial restriction of Ceduna Sub-basin scours to within c. 3 km of the
204 volcanoes, strongly suggests the volcanic edifices formed syn-incision bathymetric highs that

205 perturbed the velocity structure of the causal ocean currents. We suggest this perturbation
206 increased current turbulence and, most critically, seabed shear stress, driving localised
207 erosion of the seabed immediately adjacent to the volcanoes (Fig. 5) (e.g. O'Reilly et al.,
208 2003; MacLachlan et al., 2008). Submarine scours of broadly similar geometry, dimension,
209 and origin are observed adjacent to igneous rock-cored bathymetric highs in the Pisces Reef
210 system, Irish Sea, UK (Callaway et al., 2009), and in the Capel and Faust basins, offshore
211 eastern Australia (Rollet et al., 2012). Scours are best-developed adjacent to the tallest
212 volcanoes because only these were expressed at the paleoseabed at the onset of the ocean
213 current initiation (see below); shorter volcanoes were buried by this time, thus they lack
214 flanking scours.

215 We interpret that inclined and mounded reflections developed throughout the
216 Nullarbor Limestone represent dip-oblique and dip-parallel sections, respectively, through
217 contourite drifts (cf. Rebesco and Stow, 2001; Stow et al., 2003; Hohbein et al., 2012;
218 Rebesco et al., 2014). Sedimentary bodies like this are commonly associated with seabed
219 scours, being deposited when bottom current energy is low enough to permit sediment
220 reworking within bedforms (Fig. 5) (e.g. Stow et al., 2002). Like the scours, intra-Nullarbor
221 bedforms are spatially restricted to within a few kilometres of the vents, suggesting they too
222 formed due to volcano-driven perturbations in ocean current velocity and seabed shear stress.
223 In their case, however, an increase in seabed shear stress was only sufficient to rework
224 sediment and not deeply erode the seabed (Fig. 5).

225

226 **Implications for the paleoceanographic development of the Great Australian Bight.**

227 Although the Gnarlyknots-1a borehole penetrates the Nullarbor Formation, no
228 biostratigraphic data were collected; as a result, we cannot constrain the age of intra-
229 Nullarbor scours, associated strata, or indeed, the causal current more tightly than 'middle
230 Eocene-to-Recent'. However, biostratigraphic data from Potoroo-1, correlated into our study
231 area using regional 2D seismic profiles (DR3) does suggest that contourite-bearing strata
232 *directly* overlying Cretaceous strata are very likely pre-Quaternary, and most probably
233 Eocene (Fig. 3; see also DR1 and DR3). No paleobathymetric data (e.g. benthic foraminifera)
234 were collected in Gnarlyknots-1a, meaning we have no direct constraints on water depth
235 variations during post-Cretaceous times, and thus the depth of formation of the contourite
236 drifts remains uncertain (see also discussion in Jackson, 2012). Our relatively widely spaced
237 2D seismic reflection data also do not allow us to confidently determine if intra-Nullarbor
238 scours are preferentially developed on one, most likely the down-current (i.e. lee) side of the

239 seabed obstruction (i.e. the volcanoes), or if the associated bedforms are best-developed on
240 one, most likely the up-current side of the vents, and display down-current accretion (e.g.
241 Callaway et al., 2009; Rollet et al., 2012). Because of this, we do not know the dominant
242 direction of the causal current.

243 Notwithstanding these limitations, it is informative to discuss the implications of our
244 study for the Paleogene paleoceanographic evolution of the eastern Great Australian Bight.
245 Using biostratigraphic proxy data from the Bight and Otway basins, McGowran et al. (1997)
246 suggest the initiation of eastwards protrusion of a so-called ‘proto-Leeuwin Current’ into the
247 Great Australian Bight during the middle Eocene, with further evidence for its presence in the
248 middle Miocene (Fig. 1A; see also Feary and James, 1995, 1998). This interpretation was,
249 however, challenged by Wyroll et al. (2009), who suggest these fauna may simply record
250 locally elevated sea surface temperatures unrelated to the initiation of a plate-scale
251 thermohaline current. We here suggest middle Eocene-to-Recent contourites developed in the
252 Ceduna Sub-basin are associated with Paleogene initiation of an oceanographic current,
253 which we link to the postulated proto-Leeuwin Current, and which operated in broadly
254 similar waters depths (i.e. a few hundred metres) to the present Leeuwin Current (Fig. 5).
255 More specifically, we propose these features record late middle Eocene initiation and
256 subsequent fluctuations in the strength and erosivity of, the current. The major intra-
257 Nullarbor erosion surface (Horizon D), for example, which is best-developed immediately
258 adjacent to the volcanoes, may represent intensification or ‘waxing’ of the proto-Leeuwin
259 Current (Fig. 5). Despite a lack of age data, we tentatively suggest this erosional event, and
260 related bedforms, may be the stratigraphic expression of the Miocene Climatic Optimum-
261 related event proposed by Feary and James (1995, 1998), during which time anomalously
262 warm waters encroached eastwards into the Great Australian Bight from western Australia
263 (see also Savin et al., 1975; Gourley and Gallagher, 2004). Our interpretation of the timing of
264 onset and dynamics of the Leeuwin Current are at least broadly supported by biostratigraphic
265 data from Potoroo-1 and regional seismic data.

266 Our study shows that seismic reflection data can image erosional and depositional
267 features that provide a physical stratigraphic record of ancient ocean currents. We
268 demonstrate that by placing these features into a broad chronostratigraphic framework, we
269 can complement rather sparse micro-faunal evidence, and gain important insights into the
270 timing of onset of major ocean currents. Data limitations notwithstanding, our seismic
271 reflection-based approach does, at the very least, provide a clear hypothesis testable with
272 future scientific drilling (e.g. IODP). Seismic reflection data allow erection of a physical,

273 stratigraphic framework and remain an essential part of the paleoceanographer's toolkit.
274 Future work should focus on detailed mapping of seismic reflection datasets from, for
275 example, the western Bight Basin and Otway Basin; this may reveal similar, age-equivalent
276 current-formed stratigraphic features, thus raising the possibility that the proto-Leeuwin
277 Current extended further eastwards and influenced faunal distribution and potentially climate
278 over a wider area than currently assumed.

279

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285

286 **REFERENCES**

287

288 Boldreel, L.O.L., Andersen, M.S., and Kuijpers, A., 1998, Neogene seismic facies and deep-
289 water gateways in the Faeroe Bank area, NE Atlantic: *Marine Geology*, v. 152, p. 129-140.

290

291 Boyle, P.R., Romans, B.W., Tucholke, B.E., Norris, R.D., Swift, S.A., and Sexton, P.F.,
292 2017, Cenozoic North Atlantic deep circulation history recorded in contourite drifts, offshore
293 Newfoundland, Canada: *Marine Geology*, v. 385, p. 185-203.

294

295 Callaway, A., Smyth, J., Brown, C.J., Quinn, R., Service, M., and Long, D., 2009, The
296 impact of scour processes on a smothered reef system in the Irish Sea: *Estuarine, Coastal and
297 Shelf Science*, v. 84, p. 409–418.

298

299 Campbell, D.C., Mosher, D.C., 2015. Geophysical evidence for widespread Cenozoic bottom
300 current activity from the continental margin of Nova Scotia, Canada: *Marine Geology*, v.
301 378, p. 237-260.

302

303 Caputi, N., Chubb, C.F., and Pearce, A., 2001, Environmental effects on recruitment of the
304 western rock lobster, *Panulirus Cygnus*: *Marine and Freshwater Research*, v. 52, p. 1167-
305 1175.

306

307 Cann, J.H., and Clarke, J.A.D., 1993, The significance of *Marginopora vertebralis*
308 Foraminifera in surficial sediments at Esperance, Western Australia and in last interglacial
309 sediments in northern Spencer Gulf: *Marine Geology*, v. 111, p. 171–187.
310

311 Cresswell, G., and Goldring, T., 1980, Observations of a south-flowing current in the
312 southeastern Indian Ocean: *Deep Sea Research Part 1: Oceanographic Research Papers*, v.
313 27, p. 449-466.
314

315 Cresswell, G.R., and Domingues, C.M., 2009, The Leeuwin Current south of Western
316 Australia: *Journal of the Royal Society of Western Australia*, 92: 83–100, 2009
317

318 Davies, R.J., Cartwright, J.A., Pike, J., and Line, C., 2001, Early Oligocene initiation of
319 North Atlantic deep water formation: *Nature*, v. 410, p. 917-920.
320

321 Due, L., van Aken, H.M., Boldreel, L.O., and Kuijpers, A., 2006, Seismic and oceanographic
322 evidence of present-day bottom-water dynamics in the Lousy Bank-Hatton Bank area, NE
323 Atlantic. *Deep Sea Research Part 1: Oceanographic Research Papers*, v. 53, p. 1729-1741.
324

325 Espurt, N., Callot, J-P., Totterdell, J., Struckmeyer, H., and Vially, R., 2009, Interaction
326 between continental breakup dynamics and large-scale delta system evolution: insights from
327 the Cretaceous Ceduna delta system, Bight Basin, southern Australian margin: *Tectonics*, v.
328 28, TC6002.
329

330 Faugères, J.C., Stow, D.A.V, Imbert, P., and Viana, A., 1999, Seismic features diagnostic of
331 contourite drifts. *Marine Geology*, v. 162, p. 1-38.
332

333 Feary, D.A., and James, N.P., 1995, Cenozoic biogenic mounds and buried Miocene (?)
334 barrier reef on a predominantly cool-water carbonate continental margin, Eucla Basin,
335 western Great Australian Bight: *Geology*, v. 23, p. 427-430.
336

337 Feary, D.A., and James, N.P., 1998, Seismic Stratigraphy and Geological Evolution of the
338 Cenozoic, Cool-Water Eucla Platform, Great Australian Bight: *AAPG Bulletin*, v. 82, p. 792-
339 816.
340

341 Feng, M., Waite, A., and Thompson, P., 2009, Climate variability and ocean production in
342 the Leeuwin Current system off the west coast of Western Australia: *Journal of the Royal*
343 *Society of Western Australia*, v. 92, p. 67-81.

344

345 Gourley, T.L., and Gallagher, S.J., 2004, Foraminiferal biofacies of the Miocene warm to
346 cool climatic transition in the Port Phillip Basin, southeastern Australia: *Journal of*
347 *Foraminiferal Research*, v. 34, p. 294-307.

348

349 Henderson, G.M., 2002, New oceanic proxies for paleoclimate, *Earth and Planetary Science*
350 *Letters*, v. 203, 1-13.

351

352 Hohbein, M., Sexton, P.F., and Cartwright, J.A., 2012, Onset of North Atlantic Deep Water
353 production coincident with inception of the Cenozoic global cooling trend: *Geology*, v. 40, p.
354 255-258.

355

356 Huber, M., Brinkhuis, H., Stickley, C.E., Döös, K., Sluijs, A., Warnaar, J., Schellenberg,
357 S.A., and Williams, G.L., 2004, Eocene circulation of the Southern Ocean: Was Antarctica
358 kept warm by subtropical waters? *Paleoceanography*, v. 19, PA4026.

359

360 IPCC, 2007, *Climate Change 2007: The physical science basis. Contribution of Working*
361 *Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*
362 (eds. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M.,
363 and Miller, H.L.). Cambridge University Press, Cambridge.

364

365 Jackson, C.A-L., 2012, Seismic reflection imaging and controls on the preservation of ancient
366 sill-fed magmatic vents: *Journal of the Geological Society*, v. 169, p. 503-506.

367

368 Janocko, M., Nemeč, W., Henriksen, S. and Warchoł, M., 2013, The diversity of deep-water
369 sinuous channel belts and slope valley-fill complexes. *Marine and Petroleum Geology*, 41,
370 p.7-34.

371

372 MacLachlan, S.E., Elliott, G.M., and Parsons, L.M., 2008, Investigations of the bottom
373 current sculpted margin of the Hatton Bank, NE Atlantic: *Marine Geology*, v. 253, p. 170-
374 184.

375

376 Magee, C., Hunt-Stewart, E., and Jackson, C.A-L., 2013, Volcano growth mechanisms and
377 the role of sub-volcanic intrusions: Insights from 2D seismic reflection data: Earth and
378 Planetary Science Letters, 373, p. 41-53.

379

380 McGowran, B., Qianyu, L., Cann, J., Padley, D., McKirdy, D.M., and Shafik, S., 1997,
381 Biogeographic impact of the Leeuwin Current in southern Australia since the late Middle
382 Eocene: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 136, p. 19-40.

383

384 Müller-Michaelis, A., Uenzelmann-Neben, G., and Stein, R., 2013, A revised Early Miocene
385 age for the instigation of the Eirik Drift, offshore southern Greenland: Evidence from high-
386 resolution seismic reflection data: Marine Geology, v. 340, p. 1-15.

387

388 Posamentier, H.W. and Kolla, V., 2003, Seismic geomorphology and stratigraphy of
389 depositional elements in deep-water settings. Journal of sedimentary research, 73, p. 367-388.

390

391 O'Reilly, B., Readman, P.W., Shannon, P.M., and Jacob, A.W.B., 2003, A model for the
392 development of a carbonate mound population in the Rockall Trough based on deep-towed
393 sidescan sonar data: Marine Geology, v. 198, p. 55-66.

394

395 Rahmstorf, S., 2003, The current climate: Nature, v. 421, p. 699.

396

397 Rebesco, M., and Stow, D., 2001, Seismic expression of contourites and related deposits: a
398 preface: Marine Geophysical Researches, v. 22, p. 303–308.

399

400 Rebesco, M., Hernández-Molina, F.J., Van Rooij, D., Wählin, A., 2014. Contourites and
401 associated sediments controlled by deep-water circulation processes: state-of-the-art and
402 future considerations: Marine Geology, 352, p.111-154.

403

404 Rollet, N., McGiveron, S., Hashimoto, T., Hackney, R., Petkovic, P., Higgins, K., Grosjean,
405 E., Logan, G.A., 2012, Seafloor features and fluid migration in the Capel and Faust basins,
406 offshore eastern Australia: Marine and Petroleum Geology, v. 35, p. 269–291.

407

408 Savin, S.M., Douglas, R.G., and Stehli, F.G., 1975, Tertiary marine paleotemperatures:
409 Geological Society of American Bulletin, v. 86, p. 1499–1510.
410

411 Schofield, A., and Totterdell, J., 2008, Distribution, timing and origin of magmatism in the
412 Bight and Eucla basins: Australian Government Report, 2008/24.
413

414 Shafik, S., 1983, Calcareous nannofossil biostratigraphy: an assessment of foraminiferal and
415 sedimentation events in the Eocene of the Otway Basin, southeastern Australia: Journal of
416 Australian Geology and Geophysics, v. 8, p. 1-17.
417

418 Shafik, S., 1990, The Maastrichtian and early Tertiary record of the Great Australian Bight
419 Basin and its onshore equivalents on the Australian southern margin: a nannofossil study:
420 Bureau of Mineral Resources Journal of Australian Geology and Geophysics, v. 11, p. 473-
421 497.
422

423 Stickley, C.E., Brinhuis, H., Schellenberg, S.A., Sluijs, A., Röhl, U., Fuller, M., Grauert, M.,
424 Huber, M., Warnaar, J., and Williams, G.L., 2004, Timing and deepening of the Tasmanian
425 Gateway. *Paleoceanography*, v. 19: PA4027.
426

427 Stow, D.A.V., Faugères, J.C., Howe, J.A., Pudsey, C.J., and Viana, A.R., 2003, Bottom
428 currents, contourites and deep-sea sediment drifts: Current state-of-the-art, in Stow, D.A.V.,
429 et al., eds., *Deep-water contourite systems: Modern drifts and ancient series, seismic and
430 sedimentary characteristics: The Geological Society of London Memoir*, v. 22, p. 73–84.
431

432 Tucholke, B.E., 1979, Relationships between acoustic stratigraphy and lithostratigraphy in
433 the western North Atlantic Basin, in: Tucholke, B.E., Vogt, P.R. (Eds.), *Initial Reports of the
434 Deep Sea Drilling Project*, Vol. 43. U.S. Government Printing Office, Washington, D.C., pp.
435 827-846.
436

437 Tucholke, B.E., and Mountain, G.S., 1979, Seismic stratigraphy, lithostratigraphy and
438 paleosedimentation patterns in the North American Basin, in: Talwani, M., Hay, W., Ryan,
439 W.B.F. (Eds.), *Deep Drilling in the Atlantic Ocean: Continental Margins and
440 Paleoenvironment*, Maurice Ewing Series 3. American Geophysical Union, Washington,
441 D.C., pp. 58-86.

442

443 von Blanckenburg, F., 1999, Palaeoceanography: tracing past ocean circulation?: Science, v.
444 286, p. 1862-1863.

445

446 Wunsch, C., 2002, What is the thermohaline circulation?: Nature, v. 298, p. 1179-1181.

447

448 Wyrwoll, K-H., Greenstein, B.J., Kendrick, G.W., and Chen, G.S., 2009, The
449 palaeoceanography of the Leeuwin Current: implications for a future world. Journal of the
450 Royal Society of Western Australia, v. 92, p. 37–51.

451

452 **FIGURE CAPTIONS**

453

454 **Fig 1.** (A) Map illustrating the geographical setting of the study area. The area covered by 2D
455 seismic reflection data is outlined by a solid black line. Inset shows the key modern
456 oceanographic currents developed along the western and southern Australian margin.
457 LC=Leeuwin Current; ACC=Antarctic Circumpolar Current; WAC=West Australia Current;
458 FC=Flinders Current. OB=Otway Basin. Modified from Jackson (2012); oceanographic
459 currents from Bilj et al. (2013). Grey dashed lines indicate boundaries between sub-basins
460 forming part of the Great Australian Bight. (B) Simplified stratigraphic column based on data
461 from boreholes Gnarlyknots-1A and Potoroo-1. Key seismic horizons (A–D) and seismic
462 units (SU1-2) are indicated. The stratigraphic occurrence of intrusion and extrusive
463 components of the Bight Basin Igneous Complex (BBIC) are shown. Modified from Jackson
464 (2012).

465

466 **Fig. 2.** Time-structure map of the Horizon B (base Nullarbor Limestone) clipped where it
467 intersects Horizon C (top volcanic vents); this illustrates the distribution of volcano summits
468 (labelled 'v' and encircled by a solid white line) that rise above Horizon D, and intra-SU2
469 scours (labelled 's'). d=drifts. (A) and (B) are from the southern and northern parts of the
470 study area respectively. See Figure 1A for location of map. Light grey lines indicate seismic
471 reflection profiles. Note that the geometries of the Horizons C and D are poorly constrained
472 away from the 2D seismic reflection profiles.

473

474 **Fig. 3.** Interpreted seismic profile through the Potoroo-1 borehole, showing the age
475 constraints on the key, regionally mappable seismic horizon 'A' (top Upper Cretaceous) (see

476 also DR1 and DR2) and the development of contour current-related features (d=drifts;
477 s=scours) in the Paleocene-Eocene sequence. See Fig. 1A and DR2 for location of Potoroo-1.

478

479 **Fig. 4.** (A)–(D) Interpreted seismic profiles illustrating the geometry, scale and relationship
480 between extrusive volcanic features of the Bight Basin Igneous Complexes and intra-
481 Nullarbor Limestone contourites (i.e. scours and bedforms). Locations of the seismic lines are
482 shown in Figure 2. Note the vertical scale is provided in ms TWT and metres, based on an
483 intra-Nullarbor interval velocity of 2100 m s^{-1} . Uninterpreted versions of sections are
484 available in DRI1.

485

486 **Fig. 5.** (A–C) Schematic diagrams illustrating the evolution of intra-Nullarbor Limestone
487 contourites in the Great Australia Bight. The vertical dashed line in the ‘current strength’
488 column indicates the threshold for sediment erosion/non-deposition; these conditions occur at
489 the onset of T2.

490

491 **Data Repository Item (DR1).** Biostratigraphic and age data from Potoroo-1 (data:
492 http://dbforms.ga.gov.au/www/npm.well.summary_report?pEno=14937&pName=Potoroo%20%201&pTimescale=A&pTotalDepth=987.75&pDepthMax=987.75&pDepthMin=0&pPeriod=&pStage=&pAgeMax=65.5&pAgeMin=0&pAgeTop=0&pAgeBase=135&pTotalAge=135&pPrinterV=Yes). Data accessed on December 5th 2018. Well location: Lat -33 23' 13.571"
496 S, Long 130 46' 6.899" E. Ages are calibrated to International Chronostratigraphic Chart
497 v2018/08 of the International Stratigraphic Commission (ISC)
498 (<http://www.stratigraphy.org/index.php/ics-chart-timescale>).

499

500 **Data Repository Item (DR2).** Uninterpreted version of the seismic profile presented in Fig.
501 3.

502

503 **Data Repository Item (DR3).** Regional seismic profile between Potoroo-1, Gnarlyknots-1,
504 and our general area of study (see Figs. 3 and 4). Note the persistence of the high-amplitude,
505 top Cretaceous seismic reflection and the seismic-scale continuity of the overlying Eocene,
506 Oligocene, and Miocene rocks (see Fig. 3 and DR1). Location shown in Fig. 1A.

507

508 **Data Repository Item (DR4).** Uninterpreted versions of the seismic profiles presented in
509 Fig. 4.

Fig. 1

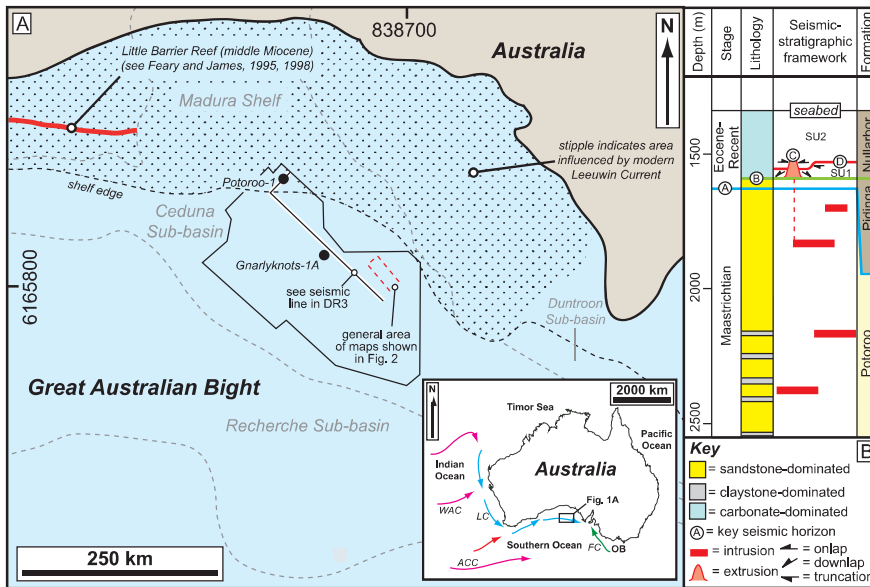


Fig. 2

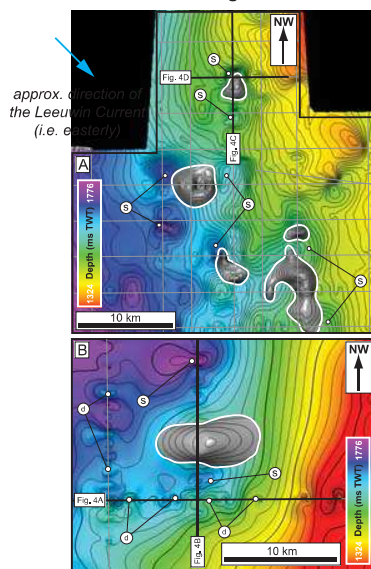


Fig. 3

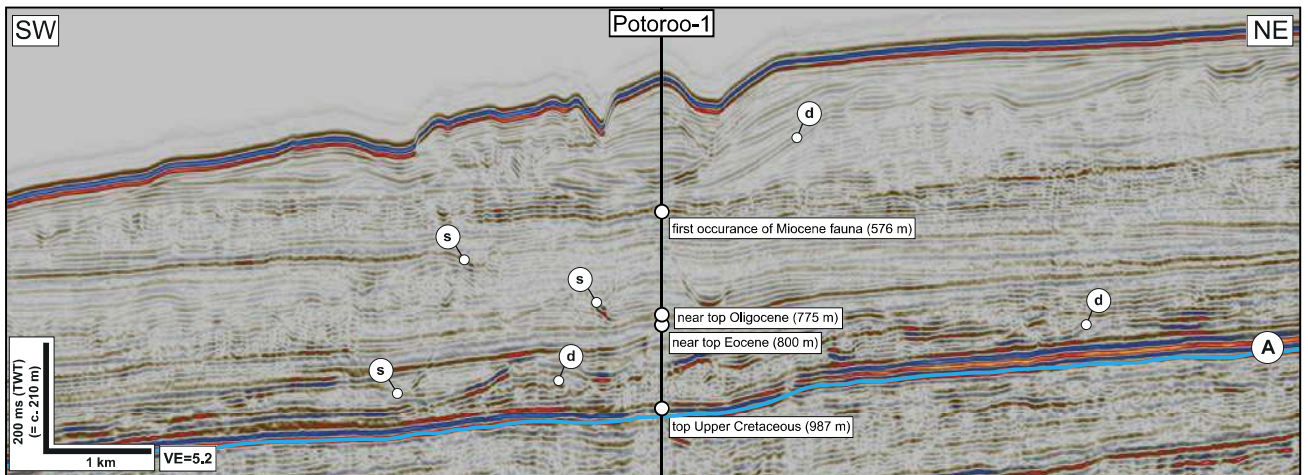


Fig. 4

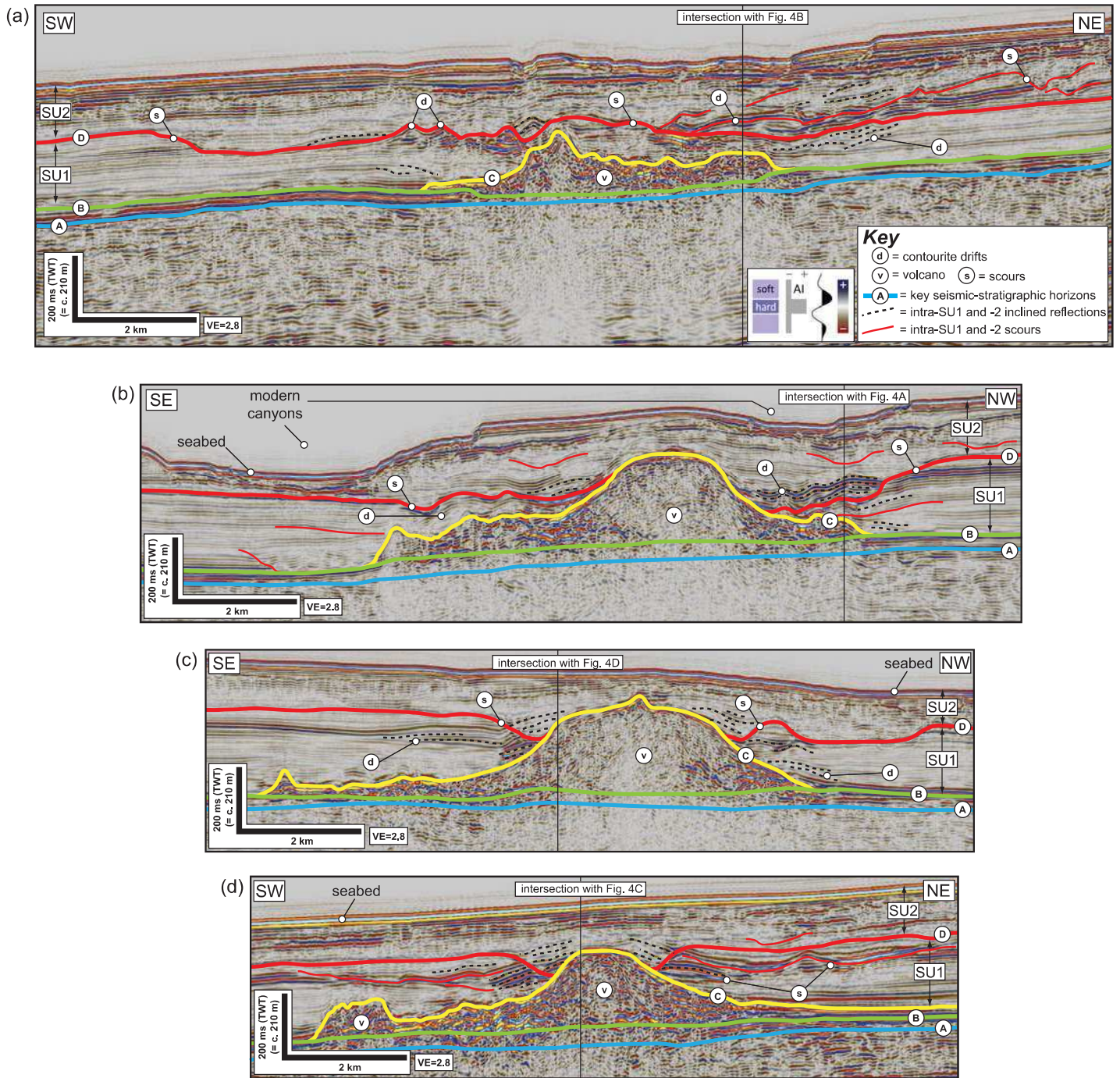


Fig. 5

