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Seismic and stratigraphic evidence for reef expansion and onset of aridity on the Northwest Shelf of Australia during the Pleistocene

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Highlights

- A previously unknown series of fossil reefs in Northwest Australia are described
- The reefs formed around 0.5 Ma with the oldest ooids in the Indian Ocean
- Reef expansion was partly due to increased Leeuwin Current intensity
- Tropical facies expanded with the onset of aridification of Australia after 0.6 Ma
- These reefs formed at the same time as the Great Barrier Reef in eastern Australia

1 **Seismic and stratigraphic evidence for reef expansion and onset of aridity on the Northwest**
2 **Shelf of Australia during the Pleistocene**

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11
12 **Abstract**

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14 Modern reef (the Great Barrier Reef and Ryukyu Reef) distribution in the Indo-Pacific region is
15
16 strongly controlled by warm currents (East Australian and Kuroshio Currents) that radiate from the
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18 Indo-Pacific Warm Pool. The modern distribution of reefs (south of 15°S) on the Western
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20 Australian shelf is related to the presence of the warm Leeuwin Current. However, the age of the
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22 reefs south of 15°S, and hence their temporal relationship to the Leeuwin Current, has been largely
23
24 unknown. Seismic and subsurface stratigraphic data show that reef growth and expansion on the
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26 Northwest Shelf of Australia began in the Middle Pleistocene (~0.5 Ma). The oldest ooids in the
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28 region are approximately synchronous with reef growth. We suggest a two stage process for the
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30 spread of reefs to higher latitudes on the Western Australian coast; first an increase in Leeuwin
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32 Current activity at approximately 1 Ma brought warm waters and a tropical biota to the region; and
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34 second, increased aridity after ~0.6 Ma led to a decline in clastic input and increased alkalinity,
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36 triggering ooid formation and reef expansion to higher latitudes associated with the switch to higher
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38 amplitude glacio-eustatic cycles at the end of the Middle Pleistocene Transition. The timing and
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40 mechanisms for reef expansion south along the Western Australian coast has implications for the
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42 origin of the Eastern Australian Middle Pleistocene Great Barrier Reef, the New Caledonia Barrier
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44 Reef and Japanese Ryukyu Reef systems.
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55 **1. Introduction**

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58 Knowledge of the timing and circumstances that triggered tropical reef development in the
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60 Indo-Pacific in the past is critical if we are to understand the resilience of modern reefs with future
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28 climate change (Frieler et al., 2012). The Great Barrier Reef and Ryukyu Reefs (Japan) initiated in
29 the Middle Pleistocene (0.4 to 1 Ma) due increased global sea level amplitude and variability
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30 (Alexander et al., 2001; Braithwaite et al., 2004; Yamamoto et al., 2006; Sakai and Jige, 2006;
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31 Montaggioni et al., 2011) possibly associated with Indo-Pacific Warm Pool expansion (Sakai,
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32 2003). Modern reefs are common in the Indian Ocean off the West coast of Australia (south of
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33 15°S) where the warm Leeuwin Current (Figure 1) extends their modern distribution to 29°S
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34 (Collins, 2002; Kendrick et al., 1991). The pre-200,000 history of these reefs is unknown (Collins,
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35 2002). Here we use seismic and stratigraphic data to show that reef expansion on the Northwest
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36 Shelf of Australia began in the Middle Pleistocene (~0.5 Ma). The oldest ooids in the region are
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37 approximately synchronous with reef growth. We suggest a two stage process for the spread of reefs
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38 to higher latitudes in the region: (1) increased Leeuwin Current activity at approximately 1 Ma
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39 brought warm waters and a tropical biota to the area; followed by (2) increased aridity after ~0.6
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40 Ma leading to a decline in clastic input and increased alkalinity, triggering ooid formation and reef
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41 expansion to higher latitudes coinciding with the onset of high amplitude Pleistocene glacio-eustatic
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42 cycles. The timing and mechanisms for reef growth off the Western Australian coast has
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43 implications for the origin of the Eastern Australian Middle Pleistocene Great Barrier, New
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44 Caledonia Barrier Reef and Ryukyu Reef systems.
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43 2. Methods

44 We have identified a series of previously unidentified fossil reefs within the carbonate dominated
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47 Neogene Delambre Formation (Wallace et al., 2003) in seismic data from the Northwest Shelf of
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51 Australia (19°S to 21°S, Figures 2 to 4). Reefs in the Delambre Formation can be identified by the
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54 presence of: bathymetric highs and irregularities on the sea floor; lenticular masses containing no
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57 reflectors; and strong velocity ‘pull-up’ structures beneath lenticular masses (cf. Ryan et al., 2009;
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61 Rosleff-Soerensen et al., 2012). To constrain the age and environmental setting of these reefs in the
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65 Delambre Formation we have used a combination of: biostratigraphic data from cuttings and
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sidewall cores (Gallagher et al., 2009), seismic stratigraphic, core and wireline log data. We

55 analysed two continuously cored engineering bores (BHC4 and BHC1) near the Angel Field (Figure
56 1) in water depths of around 80 m (Figure 5). Facies, %CaCO₃ and wireline gamma log data are
57 comparable to the LR2004 oxygen isotope record (Lisiecki and Raymo, 2005). For example the
58 lower carbonate marly facies (with relatively high gamma response) were deposited during
59 interglacial highstands and the high carbonate grainstone (with ooids, Figure 6) were deposited as
60 sea level fell to glacial conditions. Furthermore, the wireline log data for Maitland North-1 and
61 Austin-1 (Figure 5 and 7) also show a similar variability. Given this correlation, we have calibrated
62 the wireline log data for Maitland North-1 and Austin-1 using biostratigraphic data (Gallagher et al.,
63 2009) to constrain the age and climate context of the Pleistocene strata of the Delambre Formation
64 (Figure 5 and 7). Additional wireline log data and biostratigraphic data (Table 1) from other wells
65 (Figure 8) in the region are used to extend this record to the base of the Pliocene.

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3. Results

A series of drowned reefs (occurring at water depths of *ca.* 60 m) are present near Barrow Island and extend *ca.* 100 km to the northeast of the island (Figure 1 and 2). There are no modern reefs near Barrow Island, the nearest being the Ningaloo Reef (23°S, 200 km to the southwest, Figure 1) and Rowley Shoals (17°S, 300 km to the Northeast, Figure 1). Reefs are present in the upper 100 metres below sea bed (< 0.16 milliseconds) in seismic sections and lie at or above the 0.5 Ma reflector (Figure 3 and 4). Some reefs do not have a seabed bathymetric expression suggesting they are present beneath significant sediment cover (eg. Reef 2 and 7 on Figure 3). Ooids are present at log level 126.9 m (0.16 milliseconds, 0.5 Ma) in Maitland North-1 and at log level 129.1 m (0.16 milliseconds, 0.49 Ma) Maitland-1 wells just below Reef 2 at ~0.16 milliseconds on seismic line 136_07 (Figure 3). This indicates a temporal relationship between reef and ooid occurrence. Ooids are also present at two levels in cores in the Angel field (Figure 5) and where ooid occurrence may correlate to Marine Isotope Stage 3 and Stage 6.

We suggest the carbonate/siliciclastic and gamma variability of the Neogene Delambre Formation might be related to relative aridity. The aridity of Northwest Australia is alleviated by

82 the Australian summer monsoon, which delivers substantial precipitation to the northern part of the
83 continent in the Austral summer (Herold et al., 2011; Suppiah, 1992). The Australian monsoon is
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84 interpreted to be broadly controlled by global glacial–interglacial variations (Wyrwoll and Miller,
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85 2001). Strong variations in Australian monsoonal strength between glacial and interglacial periods
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86 (paced by orbital eccentricity and precession) have been documented over the last 460 kyrs from
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87 13°S off Northwest Australia (Kawamura et al., 2006), with stronger monsoonal (wet) conditions
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100 If the gamma log and sedimentation model is applied to the Plio-Pleistocene strata of the Northwest
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101 Shelf, the upward decrease in gamma values (Figure 5, 7 and 8) may be interpreted to reflect an
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104 Ma punctuated by a 0.4 Ma period of high gamma (precipitation) variability followed by upward
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105 increasing aridity after 0.6 Ma (Figure 9).

106 4. Discussion

107 A possible pre-condition for Indo-Pacific reef expansion during the Pleistocene may be Indo-Pacific
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108 Warm Pool expansion during the Middle Pleistocene Transition at around 1 Ma (Sakai, 2003). The

109 Great Barrier Reef, for example, expanded to its present position at 600±280 ka or from 560 to 670
110 ka (Alexander et al., 2001; Dubois et al., 2008) and the Ryukyu reefs migrated northward to their
111 present latitude by the middle Pleistocene at from ~1.07 to 0.8 Ma (Sakai and Jige, 2006;
112 Yamamoto et al., 2006). Barrier reefs initiated in New Caledonia by Marine Isotope Stage (MIS)
113 11, 400,000 years ago (Montaggioni et al., 2011). These reefs expanded during a period of
114 enhanced high amplitude glacio-eustatic sea level variability during the mid-Brunhes when flooding
115 of previously exposed karst or fluvial surfaces enhanced reef development (Droxler and Jorry,
116 2013). On the Northwest Shelf reefs and associated ooids appeared at around 0.5 Ma (close to the
117 Great Barrier Reef ages and New Caledonia Barrier reef expansion estimates). It is likely that
118 glacio-eustatic sea level variability was a factor in reef expansion and ooid occurrence on the
119 Northwest Shelf, however, the regional setting of the Northwest Shelf at the fringes of the Indo-
120 Pacific Warm Pool is complicated as it is directly downstream of the Indonesian Throughflow
121 (Figure 1). The Indonesian Throughflow has a strong control on the Late Neogene
122 paleoceanography of the Northwest shelf (Gallagher et al., 2009), it also controls regional reef
123 development via the Leeuwin Current (Kendrick et al., 1991). We propose several inter-related
124 factors have influenced reef development and tropical carbonate deposition on the Northwest Shelf:
125 the Leeuwin Current, carbonate supersaturation, aridity and enhanced middle Pleistocene sea level
126 variability.

127 128 **4.1 The Leeuwin Current**

129 The distribution and timing of modern coral reef development off West Australia is intimately
130 related to the Leeuwin Current (Kendrick et al., 1991). The Leeuwin Current (Figure 1) is the only
131 south-flowing eastern boundary current in the southern hemisphere. Its past intensity is related to
132 Indonesian Throughflow connectivity and Indo-Pacific Warm Pool history (Gallagher et al., 2009).
133 The Leeuwin Current extends modern tropical coral reef development to 29°S - the Houtman-
134 Abrolhos reefs (Collins et al., 1993; Figure 1) and the tropical/subtropical transition as far south as
135 Rottneest Island at 33°S (Greenstein and Pandolfi, 2008). While the Late Pleistocene record and

136 modern oceanography of the Leeuwin Current is well known (see Cresswell, 1991; Pearce, 2009
137 and references therein) the pre-late Pleistocene history of this current off the west coast of Australia
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138 is not well known (Kendrick et al., 1991; Wyroll et al., 2009). Kendrick et al. (1991) used mollusc
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139 assemblages in marine carbonate strata near Perth Western Australia, to suggest that the Leeuwin
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140 Current was inactive or weak in the Early Pleistocene and became more intense by the Middle
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141 Pleistocene. Biogeographic studies using foraminifera on the Northwest Shelf have shown that
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142 there was intermittent and restricted Indonesian Throughflow (and Leeuwin Current) from ~4 to 1.6
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143 million years ago (Gallagher et al., 2009). Thereafter, the Leeuwin Current became more intense
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144 from 1 to 0.8 Ma after which it reached its modern state. It would therefore appear that based on
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145 the history of the Leeuwin Current alone, by 0.8 Ma, regional oceanic conditions should have been
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146 suitable for reef development. However, it wasn't until ~0.5 Ma that reefs and ooids appeared on
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147 the Northwest Shelf (south of 18°S), suggesting that some other factor influenced reef growth.
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148 26 27 28 149 **4.2 Carbonate supersaturation** 30

150 Warm waters supersaturated in carbonate are required marine ooid formation. Ooids are spherical to
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151 oval coated grains that typically form in shallow (<5 m) agitated, tide-dominated tropical
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152 environments with elevated evaporation and salinity (Simone, 1981; James et al., 2004). Globally,
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153 marine subtropical to tropical ooids have been interpreted to be direct evidence of physiochemical
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154 precipitation from sea water during periods of elevated seawater alkalinity and supersaturation
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155 (Simone, 1981; Rankey and Reeder, 2009). Rankey and Reeder (2009) acknowledge the rarity of
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156 ooids in modern and pre-Holocene deposits in the Pacific region and suggest that this is due the
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157 relative lack of regions with sufficiently elevated carbonate supersaturation. There is a similar
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158 dearth of ooids in the Indian Ocean (Braithwaite, 1994) for reasons that are enigmatic. One factor
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159 that may account for their rarity in the Indo-Pacific is the absence of particular favourable
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160 conditions required for their formation, for example, ooids accumulate during relatively slow
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161 transgressions on flat carbonate platforms (Hearty et al., 2010). So, if the sea level rise is too fast
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162 on a flat platform, they will not form (Hearty et al., 2010). The oldest ooids previously described
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163 from the Indian Ocean formed from 15.4 to 12 kyrs ago (James et al., 2004) on a low angle ramp on
164 the Northwest Shelf (from 17° to 21°S). James et al. (2004) attributed their formation to increased
165 Leeuwin Current activity (*ca.* 12 ka) as sea levels rose after the last glacial maximum (LGM).
166 Ooids are present in the carbonate supersaturated shallow water of the arid environment in Shark
167 Bay at 25.5°S (Davies, 1970). Other ooids on the Northwest Shelf at 18°30'S formed 3.3 kyr ago
168 during a period of slow sea level rise (Hearty et al., 2006). In the Maldives ooids formed during the
169 early cooling and late warming phase of the last glacial cycle (Braithwaite, 1994). We find
170 evidence on the Northwest Shelf of ooids being deposited back to approximately 0.5 Ma, suggesting
171 that increased regional alkalinity/sea surface evaporation began at this time associated with periods
172 of slow sea level rise in a flat tropical carbonate ramp setting.

174 4.3 Aridity

175 The relative timing of the onset of aridification of Australia during the late Neogene Australia is
176 well known (McLaren and Wallace, 2010; McLaren et al., 2011; 2012; 2014). In Southeast
177 Australia, wetter Pliocene conditions (Gallagher et al., 2003) were replaced in a step-wise manner
178 by more arid conditions by 1.5 Ma (McLaren et al., 2011). In Southwest Australia, the
179 disappearance of Lake Lefroy at around 500 ka signifies increased aridity (Zheng et al., 1998). In
180 Northwest Australia a sparsely sampled offshore pollen record from 6-1.8 Ma at Ocean Drilling
181 Program Site 765 at 15°S shows progressive drying from 5-3 Ma, especially since 1.8 Ma (McMinn
182 and Martin, 1992). Further evidence of heightened aridity at *ca.* 1 Ma is represented by the
183 initiation of sand dune fields in the Australian monsoon influenced central Australian Simpson
184 Desert (Fujioka et al., 2009). Onshore, the progressive demise of megalakes in northwestern
185 Australia after 300 kyrs is interpreted to reflect increased drying and reduction of monsoonal
186 activity (Bowler et al., 2001) in the Middle Pleistocene.

187 If the patterns in our gamma data reflect relative precipitation and runoff from the Australian
188 continent through time across the Northwest Australian Shelf, then Australian Monsoon intensity
189 may have decreased in two steps, with drier conditions after ~1.5 Ma followed by a switch to

190 modern aridity and monsoonal conditions after ~0.6 Ma (Figure 5, 6 and 9). The first of these
191 drying phases corresponds to the disappearance of megalakes and the onset of Early Pleistocene
192 aridification in Southeast Australia (McLaren and Wallace, 2010; Sniderman et al., 2009). The
193 upward increase in aridity after this time in Northwest Australia also coincides with the expansion
194 of extensive sand dune deposits formed in central Australia ~ 1 Ma (Fujioka and Chappell, 2010).
195 The final phase of aridification after ~0.6 Ma and decrease in monsoonal intensity on the Northwest
196 Shelf correlates to the drying of Lake Lefroy in Southwest Australia (Zheng et al., 1998) and the
197 switch from an oxide to carbonate dominated weathering regime in the southern half of Australia
198 during the Middle Pleistocene (Pillans and Bourman, 2001). We suggest this final aridification
199 phase and a strong Leeuwin Current facilitated the southerly expansion of tropical carbonates (reef
200 and ooids) off the west coast of Australia during the Middle Pleistocene (Figure 9).

202 **5. Pleistocene sea level variability and global reef expansion**

203 Reef expansion on the Northwest Shelf followed the first (MIS 16 ~620,000 years ago) of the high
204 amplitude glacio-eustatic cycles at the end the Mid Pleistocene Transition (MPT: Figure 10). The
205 reefs may have been deposited during MIS 15 or 13. Elsewhere, in the Indo-Pacific reef expansion
206 (the Great Barrier Reef, Ryukyu Reefs and New Caledonian Barrier Reef) is interpreted to have
207 been related to a combination of the initiation of high amplitude sea level variability during the
208 MPT in the period from 1 million to 400,000 years and tectonic subsidence variations (Montaggioni
209 et al., 2011). In the southern Caribbean, the Belize barrier reef also initiated during the mid to late
210 Brunhes (Gischler et al., 2010; Droxler and Jorry, 2013). Droxler and Jorry (2013) suggest flooding
211 of Pleistocene lowstand tropical fluvial regions or carbonate palaeokarsts during the unique
212 transgression in the lead up to the MIS 11 (400,000 years) interglacial facilitated global barrier reef
213 expansion (Droxler et al., 2003). However, estimates for the age for reef expansion vary (Figure
214 10) and most initiate before MIS 11. For example, Ryukyu reef initiation occurred from 1.07
215 million to 800,000 years ago (Sakai and Jige, 2006; Yamamoto et al., 2006). Estimates for GBR
216 initiation range from 400 to 670,000 years (Alexander et al., 2001; Braithwaite et al., 2004; Dubois

217 et al., 2008). The modern Belize Barrier reef expanded in the period from MIS 15 to MIS 11
218 (620,000 to 400,000 years ago, Droxler and Jorry, 2013). While all of these estimates coincide
219 with the onset of the largest glacio-eustatic cycles in the Pleistocene, we suggest regional factors
220 also control the variation in reef expansion and propagation. The northerly extension of the modern
221 Ryukyu Reefs is strongly controlled by the Kuroshio Current (Iryu et al., 2006), in the past the
222 Ryukyu Reef front migrated to more southerly latitudes in glacial periods, and migrated north
223 during interglacials. The Kuroshio Current reached its present latitudinal limit and intensity during
224 Pliocene (after 3 Ma) due to an enhanced North Pacific Gyre. The gyre intensification was related
225 to the onset of the Northern Hemisphere Ice Sheet and closure of the Isthmus of Panama (Gallagher
226 et al., 2009). It is possible that North Pacific Gyre and Kuroshio Current intensified in a step-wise
227 way as the magnitude of glacio-eustatic variability increased through the MPT leading to reef
228 expansion by 800,000 year ago. In the Coral Sea average sea surface temperatures remained
229 relatively constant and greater than 20°C over the last 1.6 million years (Russon et al., 2011)
230 suggesting GBR and New Caledonia Barrier Reef expansion was not primarily controlled by this
231 factor (Russon, 2011). However, glacial sea surface temperatures dropped below 18°C (Russon,
232 2011), the temperature limit for reef development (Kleypas et al., 1999), suggesting sea level
233 variability was not the only influence affecting reef development in this area. Furthermore,
234 Montaggioni et al. (2011) reviewed the role of climate change on reef development in the western
235 Pacific and Caribbean and suggest its role is not clear, however, these authors conclude that climate
236 conditions appear not to have been suitable for enhanced coral development during the early and
237 middle Pleistocene.

239 6. Conclusions

240 A series of Pleistocene drowned reefs (south of 18°S) are described on the Northwest Shelf of
241 Australia for the first time. Seismic and subsurface stratigraphic data suggest that these reefs
242 initiated in the Middle Pleistocene ~0.5 Ma associated with the oldest oolites in the Indian Ocean.
243 The expansion of reefs (the Great Barrier and Ryukyu Reefs) in the Indo-Pacific may have been

244 related Indo-Pacific Warm Pool expansion during the Middle Pleistocene Transition. However, the
245 majority of reefs expanded in the Indo-Pacific and the Caribbean following the onset of high
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246 amplitude glacio-eustatic cycles of the Middle Pleistocene Transition after 650,000 year ago.
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247 During this time it is postulated that luxuriant reefs advanced over large tracts of previously
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248 exposed ramp surfaces during flooding events leading to global reef expansion. However, other
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249 regional factors influence reef development and global reef diachroneity. Kuroshio Current
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250 intensity influences the Ryukyu Reef development and this current may have facilitated its early
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251 expansion (after 1 Ma). Sea surface temperatures during glacial phases may have limited reef
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252 development in the Coral Sea (the GBR and New Caledonia Barrier Reef). In addition, the regional
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253 setting of the Northwest Shelf is complicated by the degree of Indonesian Throughflow restriction
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254 which controls the relative intensity of warm south flowing Leeuwin Current, a current that controls
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255 the present reef distribution off western Australia. We suggest an increase in Leeuwin Current
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256 activity at ~1 Ma may have been followed by a reduction in Australian Monsoon intensity (and
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257 increased aridity) after 0.6 Ma leading to supersaturated conditions appropriate for reef expansion
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258 and ooid formation (Figure 9). Tropical carbonate deposition on the Northwest Shelf was also
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259 likely to have been influenced by the inception of the first high amplitude glacio-eustatic cycles
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260 during the Middle Pleistocene Transition, however, the relative intensity of Indonesian
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261 Throughflow, Indo-Pacific Warm Pool variability and continental aridity exerted a strong regional
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262 control on their evolution and expansion into higher latitudes.
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263 43 44 45 264 **7. Acknowledgements**

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48
291
49
50
292
52
293
54
55
294
57
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8. References

- Alexander, I., Andres, M.S., Braithwaite, C.J.R., Braga, J.C., Cooper, M.J., Davies, P.J., Elderfield, H., Gilmour, M.A., Kay, R.L.F., Kroon, D., MacKenzie, J.A., Montaggioni, L.F., Skinner, A., Thompson, R., Vasconcelos, C., Webster, J., Wilson, P.A., 2001. New constraints on the origin of the Australian Great Barrier Reef; results from an international project of deep coring. *Geology* 29, 483-486.
- Bowler, J.M., Wyrwoll, K.H., Lu, Y., 2001. Variations of the northwest Australian summer monsoon over the last 300,000 years: the paleohydrological record of the Gregory (Mulan) Lakes System. *Quaternary International* 83, 63-80.
- Braithwaite, C.J.R., 1994. Quaternary oolites in the Indian Ocean. *Atoll Research Bulletin* 420, 10.
- Carter, R.M., Gammon, P., 2004. New Zealand Maritime Glaciation: Millennial-Scale Southern Climate Change Since 3.9 Ma. *Science* 304, 1659-1662.
- Collins, L.B., 2002. Tertiary foundations and quaternary evolution of coral reef systems of australia's North West Shelf, In: Keep, M., Moss, S.J. (Eds.), *The sedimentary basins of Western Australia*. Petroleum Exploration Society of Australia, Perth, pp. 129-152.
- Collins, L.B., Zhao, J.-X., Wryoll, Z.R., Hatcher, B.G., Playford, P.E., Eisenhauer, A., Chen, J.H., Wasserburg, G.J., Bonani, G., 1993. Holocene growth history of a reef complex on a cool-water carbonate margin: Easter Group of the Houtman Abrolhos, Eastern Indian Ocean. *Marine Geology* 115, 29-46.
- Cresswell, G.R., 1991. The Leeuwin Current - observations and recent models. *Journal of the Royal Society of Western Australia* 74, 1-14.
- Davies, G., 1970. Carbonate bank sedimentation, eastern Shark Bay, western Australia. *Carbonate Sedimentation and Environments, Shark Bay, Western Australia: American Association of Petroleum Geologists, Memoir* 13, 85-168.

297 deMenocal, P., Bristow, J., Stein, R., 1992. Paleoclimatic applications of downhole logs Plio-
298 Pleistocene results from Hole 798B, Sea of Japan. Proceedings ODP, Scientific Results+ 128
1
299 127, 393-408.
3
4
300 Droxler, A. W., Alley, R. B., Howard, W. R., Poore, R. Z., and Burckle, L. H., 2003, Unique and
6
301 exceptionally long interglacial Marine Isotope Stage 11: window into Earth warm future
8
302 climate: Earth's Climate and Orbital Eccentricity: The Marine Isotope Stage 11 Question, p.
10
303 1-14.
13
304 Droxler, A. W., and Jorjy, S. P. J., 2013, Deglacial Origin of Barrier Reefs Along Low-Latitude
15
305 Mixed Siliciclastic and Carbonate Continental Shelf Edges: Annual Review of Marine
18
306 Science, v. 5, p. 165-190.
20
307 Dubois, N., Kindler, P., Spezzaferri, S., and Coric, S., 2008, The initiation of the southern central
22
308 Great Barrier Reef: New multiproxy data from Pleistocene distal sediments from the Marion
25
309 Plateau (NE Australia): Marine Geology, v. 250, no. 3, p. 223-233.
27
28
310 Frieler, K., Meinshausen, M., Golly, A., Mengel, M., van der Merwe, K., Donner, S., Hoegh-
30
311 Guldberg, O., 2012. Majority of Coral Reefs at Risk already below 1.5 C of Global Warming.
32
312 Nature Climate Change 3, 165-170.
35
313 Fujioka, T., Chappell, J., 2010. History of Australian aridity: chronology in the evolution of arid
37
314 landscapes. Geological Society, London, Special Publications 346, 121-139.
38
40
315 Fujioka, T., Chappell, J., Fifield, L.K., Rhodes, E.J., 2009. Australian desert dune fields initiated
42
316 with Pliocene-Pleistocene global climatic shift. Geology 37, 51-54.
43
44
45
317 Gallagher, S.J., Greenwood, D.R., Taylor, D., Smith, A.J., Wallace, M.W., Holdgate, G.R., 2003.
47
318 The Pliocene climatic and environmental evolution of southeastern Australia; evidence from
48
49
50
319 the marine and terrestrial realm. Palaeogeography, Palaeoclimatology, Palaeoecology 193,
52
320 349-382.
53
54
55
321 Gallagher, S.J., Wallace, M.W., Li, C.L., Kinna, B., Bye, J.T., Akimoto, K., Torii, M., 2009.
57
322 Neogene history of the West Pacific Warm Pool, Kuroshio and Leeuwin currents.
59
323 Paleoceanography 24, PA1206, doi:10.1029/2008PA001660, 2009
60
61
62
63
64
65

324 Gischler, E., Ginsburg, R.N., Herriez, J.O., Prasad, S., 2010, Mixed carbonates and siliciclastics in
325 the Quaternary of southern Belize: Pleistocene turning points in reef development controlled
1
326 by sea-level change: *Sedimentology*, v. 57, no. 4, p. 1049-1066.
3
327 Greenstein, B.J., Pandolfi, J.M., 2008. Escaping the heat: range shifts of reef coral taxa in coastal
6
328 Western Australia. *Global Change Biology* 14, 513-528.
8
329 Hearty, P.J., O'Leary, M., Donald, A., Lachlan, T., 2006. The enigma of 3400 years BP coastal
10
330 oolites in tropical northwest Western Australia, why then, why there? *Sedimentary Geology*
11
331 186, 171-185.
13
332 Hearty, P. J., Webster, J. M., Clague, D. A., Kaufman, D. S., Bright, J., Southon, J., and Renema,
16
333 W., 2010, A pulse of ooid formation in Maui Nui (Hawaiian Islands) during Termination I:
18
334 *Marine Geology*, v. 268, no. 1, p. 152-162.
20
335 Herold, N., Huber, M., Greenwood, D.R., Mueller, R.D., Seton, M., 2011. Early to Middle Miocene
23
336 monsoon climate in Australia. *Geology* 39, 3-6.
25
337 Hesse, P.P., Magee, J.W., Van Der Kaars, S., 2004. Late Quaternary climates of the Australian arid
27
338 zone: a review. *Quaternary International* 118, 87-102.
28
339 Iryu, Y., Matsuda, H., Machiyama, H., Piller, W. E., Quinn, T. M., and Mutti, M., 2006,
30
340 Introductory perspective on the COREF Project: *Island Arc*, v. 15, no. 4, p. 393-406.
32
341 James, N.P., Bone, Y., Kyser, T.K., Dix, G.R., Collins, L.B., 2004. The importance of changing
33
342 oceanography in controlling late Quaternary carbonate sedimentation on a high-energy,
34
343 tropical, oceanic ramp; north-western Australia. *Sedimentology* 51, 1179-1205.
35
344 Kawamura, H., Holbourn, A., Kuhnt, W., 2006. Climate variability and land-ocean interactions in
36
345 the Indo Pacific Warm Pool; a 460-ka palynological and organic geochemical record from the
37
346 Timor Sea. *Marine Micropaleontology* 59, 1-14.
38
347 Kendrick, G.W., Wyrwoll, K.-H., Szabo, B.J., 1991. Pliocene-Pleistocene coastal events and history
39
348 along the western margin of Australia. *Quaternary Science Reviews* 10, 419-439.
40
349 Kleypas, J. A., McManus, J. W., and Menez, L. A. B., 1999, Environmental limits to coral reef
41
350 development: where do we draw the line?: *American Zoologist*, v. 39, no. 1, p. 146-159.
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

351 Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic
352 delta (super 18) O records. *Paleoceanography* 20, no.1, 17.

353 Magee, J.W., Miller, G.H., Spooner, N.A., Questiaux, D., 2004. Continuous 150 ky monsoon record
354 from Lake Eyre, Australia: Insolation-forcing implications and unexpected Holocene failure.
355 *Geology* 32, 885-888.

356 McLaren, S., Wallace, M.W., 2010. Plio-Pleistocene climate change and the onset of aridity in
357 southeastern Australia. *Global and Planetary Change* 71, 55-72.

358 McLaren, S., Wallace, M.W., Gallagher, S.J., Miranda, J.A., Holdgate, G.R., Gow, L.J., Snowball,
359 I., Sandgren, P., 2011. Palaeogeographic, climatic and tectonic change in southeastern
360 Australia: the Late Neogene evolution of the Murray Basin. *Quaternary Science Reviews* 30,
361 1086-1111.

362 McLaren, S., Wallace, M.W., Reynolds, T., 2012. The Late Pleistocene evolution of palaeo
363 megalake Bungunna, southeastern Australia: A sedimentary record of fluctuating lake
364 dynamics, climate change and the formation of the modern Murray River. *Palaeogeography,
365 Palaeoclimatology, Palaeoecology*, v. 317-318, p. 114-127.

366 McLaren, S.N., Wallace, M.W., Gallagher, S.J. and Wagstaff, B.E., Tosolini, A-M, P. 2014,
367 Chapter 12, The development of a climate – an arid continent with wet fringes, in, Prins, H. &
368 Gordon, I. eds., *Invasion Biology and Ecosystem Theory* (Cambridge University Press), 256-
369 280 ISBN: 9781107035812

370 McMinn, A., Martin, H., 1992. Late Cenozoic pollen history from Site 765, eastern Indian Ocean.
371 *Proceedings of the Ocean Drilling Program Scientific Results* 123, 421-427.

372 Miller, K. G., Mountain, G. S., Wright, J. D., and Browning, J., 2011, Sea level and ice Volume
373 Variations: *Oceanography*, v. 24, no. 2, p. 40-53.

374 Montaggioni, L. F., Cabioch, G., Thouveny, N., Frank, N., Sato, T., and Semah, A.-M., 2011,
375 Revisiting the Quaternary development history of the western New Caledonian shelf system:
376 from ramp to barrier reef: *Marine Geology*, v. 280, no. 1, p. 57-75.

377 Pearce, A., 2009. Introduction: some historical "milestones" in the Leeuwin Current, and the
378 Leeuwin Current Symposium 2007. *Journal of the Royal Society of Western Australia* 92,
1
379 31-36.
3
380 Pillans, B., Bourman, R., 2001. Mid Pleistocene arid shift in southern Australia, dated by
4
5
6
381 magnetostratigraphy. *Soil Research* 39, 89-98.
8
382 Rankey, E.C., Reeder, S.L., 2009. Holocene ooids of Aitutaki Atoll, Cook Islands, South Pacific.
9
10
11
383 *Geology* 37, 971-974.
13
384 Rohling, E., Grant, K., Bolshaw, M., Roberts, A., Siddall, M., Hemleben, C., and Kucera, M., 2009,
14
15
16
385 Antarctic temperature and global sea level closely coupled over the past five glacial cycles:
17
18
386 *Nature Geoscience*, v. 2, no. 7, p. 500-504.
20
21
387 Rosleff-Soerensen, B., Reuning, L., Back, S., and Kukla, P., 2012. Seismic geomorphology and
22
23
24
388 growth architecture of a Miocene barrier reef, Browse Basin, NW-Australia: Marine and
25
26
389 *Petroleum Geology*, 29, 233-254.
28
390 Russon, T. F., 2011, Paleooceanography of the southern Coral Sea across the Mid-Pleistocene
29
30
31
391 Transition. Unpublished PhD Thesis, The University of Edinburgh, 283 pp.
33
392 Russon, T., Elliot, M., Sadekov, A., Cabioch, G., Corregge, T., and De Deckker, P., 2011, The mid-
34
35
36
393 Pleistocene transition in the subtropical southwest Pacific: *Paleoceanography*, v. 26, no. 1, p.
37
38
394 PA1211.
40
395 Ryan, G.J., Bernadel, G., Kennard, J.M., Jones, A.T., Logan, G.A., Rollet, N., 2009. A precursor
41
42
43
396 extensive Miocene reef system to the Rowley Shoals reefs, WA: evidence for structural
44
45
397 control of reef growth or natural hydrocarbon seepage? *APPEA Journal* 49, 337-363.
46
47
398 Sakai, S., 2003. Shallow-water carbonates record marginal to open ocean Quaternary
48
49
50
399 paleoceanographic evolution. *Paleoceanography* 18, 1088, doi:10.1029/2002PA000852, 2003.
51
52
400 Sakai, S., and Jige, M., 2006, Characterization of magnetic particles and magnetostratigraphic
53
54
401 dating of shallow-water carbonates in the Ryukyu Islands, northwestern Pacific: *Island Arc*, v.
55
56
402 15, no. 4, p. 468-475.
57
58
403 Simone, L., 1981. Ooids: A review. *Earth Science Reviews* 16, 319-355.
60
61
62
63
64
65

- 404 Sniderman, J., Porch, N., Kershaw, A., 2009. Quantitative reconstruction of Early Pleistocene
405 climate in southeastern Australia and implications for atmospheric circulation. *Quaternary*
1
406 *Science Reviews* 28, 3185-3196.
3
- 407 Suppiah, R., 1992. The Australian summer monsoon: a review. *Progress in Physical Geography* 16,
6
408 283.
8
- 409 van der Kaars, S., De Deckker, P., Gingele, F.X., 2006. A 100,000-year record of annual and
10
410 seasonal rainfall and temperature for northwestern Australia based on a pollen record
11
13
411 obtained offshore. *Journal of Quaternary Science* 21, 879-889.
15
- 412 Wade, B.S., Pearson, P.N., Berggren, W.A., Palike, H., 2011. Review and revision of Cenozoic
16
18
413 tropical planktonic foraminiferal biostratigraphy and calibration to the geomagnetic polarity
20
414 and astronomical time scale. *Earth-Science Reviews* 104, 111-142.
21
22
23
- 415 Wallace, M., Condilis, E., Powell, A., Redfearn, J., Auld, K., Wiltshire, M., Holdgate, G.,
25
416 Gallagher, S., 2003. Northwest Shelf--New ideas, new discoveries-Geological controls on
26
28
417 sonic velocity in the Cenozoic carbonates of the Northern Carnarvon Basin, North West Shelf,
30
418 Western Australia. *APPEA Journal-Australian Petroleum Production and Exploration*
31
32
419 *Association* 43, 385-400.
33
35
- 420 Wallace, M.W., Holdgate, G.R., Daniels, J., Gallagher, S.J., Smith, A., 2002. Sonic velocity,
37
38
421 submarine canyons, and burial diagenesis in Oligocene-Holocene cool-water carbonates,
40
422 Gippsland Basin southeast Australia. *AAPG Bulletin* 86, 1593-1607.
42
43
- 423 Wyrwoll, K.H., Miller, G.H., 2001. Initiation of the Australian summer monsoon 14,000 years ago.
44
45
424 *Quaternary International* 83, 119-128.
47
- 425 Wyrwoll, K.H., Greenstien, B.J., Kendrick, G.W. and Chen, G.S. 2009. the palaeoceanography of
48
49
50
426 the Leeuwin Current: implications for a future world. *Journal of the Royal Society of*
52
427 *Western Australia* 92, 37-51.
54
- 428 Yamamoto, K., Iryu, Y., Sato, T., Chiyonobu, S., Kenichi, S., Abe, E., 2006. Responses of coral
57
429 reefs to increased amplitude of sea-level changes at the mid-Pleistocene climate transition.
59
60
430 *Palaeogeography, Palaeoclimatology, Palaeoecology* 241, 160-175.
61
62
63
64
65

431 Zheng, H., Wyrwoll, K.H., Li, Z., McA Powell, C., 1998. Onset of aridity in southern Western
432 Australia, - a preliminary palaeomagnetic appraisal. Global and Planetary Change 18, 175-
1
433 187.
3

4
434

5
435

6
436

7
437

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438

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437 **List of Figures**

438 Figure 1. The location of the Northwest Shelf of Australia and its relationship to Indo-Pacific
1 palaeoceanography (a) The bathymetry of the Northwest Shelf (NWS) from the Geoscience
439 2 Australia: *Australian bathymetry and topography grid, June 2009*
3 4
440 5 (<http://www.ga.gov.au/meta/ANZCW0703013116.html#citeinfo>). The path of the Leeuwin
6 7 Current is shown along with the position of the nearest Recent reefs (the Houtman-Abrolhos,
441 8 Ningaloo Reefs and Rowley Shoals) and the Drowned Reefs described in this paper (Box =
9 10 Figure 2). The position of the Angel field (An) is indicated. (b) Inset map of the oceanography
442 11 of the Indo-Pacific Warm Pool (IPWP). WAC = West Australian Current, ITF = Indonesian
443 12 Throughflow, RR = Ryukyu Reefs and GBR = Great Barrier Reef. The 28°C isotherm is
444 13 shown, the red currents are warm and the blue cold (Gallagher et al., 2009).
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446 26 Figure 2. (a) The bathymetry of the Barrow Island region (for location see Figure 1), (b) A map of
27 28 the drowned reefs of the Northwest Shelf of Australia (NWS). Wells used in stratigraphy: A1
447 29 = Austin-1, F1 = Fisher-1, G2/G6 = Goodwyn-2/6, M1 = Maitland-1, MN1 = Maitland North-
30 31 1, T1 = Tryal Rocks-1, Ti1 = Tidepole-1, W2 = Wilcox-2 and WT1 = West Tryal Rocks-1.
32 33
448 34 The reefs with the black outline have bathymetric expression, those without are in the
35 36 subsurface and are interpreted from seismic data. The position of four interpreted seismic
449 37 sections are indicated (Figure 3 and 4).
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450 46 Figure 3. Seismic data from the Northwest Shelf. The 0.5 Ma (blue), 1.0 Ma (yellow) and 1.8 Ma
47 48 (red) reflectors are indicated. The location of the drowned reefs (light green with blue
451 49 numbers) and the seismic sections are shown on Figure 2. The age of the reflectors are based
50 51 on the age/depth/TWT (Two Travel Time) well data in Table 1.
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453 59 Figure 4. Seismic section D-D' from the Northwest Shelf. The 0.5 Ma (blue), 1.0 Ma (yellow) and
60 61 2 Ma (red) reflectors are indicated. The location of the drowned reefs (light green with blue
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464 numbers) and the seismic sections are shown on Figure 2. The age of the reflectors are based
465 on the age/depth/TWT (Two Travel Time) well data in Table 1.

466
467 Figure 5. A correlation of **a.** Austin-1; **b.** Maitland North-1 wireline logs, **d.**, **e.** and **f.** Angel field
468 well data, with the **c.** LR2004 stack (Lisiecki and Raymo, 2005). The facies and %carbonate
469 (see Wallace et al., (2002) for %Carbonate technique) of two cores **d.** BHC4 (19.491021°S,
470 116.597943°W) and **e.** BHC1 (19.490588°S, 116.597792°W) near the Angel field are shown.
471 These cores are close to the Angel-4 **f.** well (19.48121°S, 116.61333°W). In the Angel field
472 the facies of Marine Isotope Stages (MIS) 7 and 5e yield lower %carbonate (sandy marl facies
473 and gamma maxima in Angel-4) compared to MIS 5 and 6 (carbonate-rich, gamma minima in
474 Angel-4). Ooids are present in the grainstone of MIS 6 and 3 in BHC4. Sea bed (s.b.) depths
475 are approx. 80 m in BHC1, BHC4 and Angel-4. Peaks in the gamma profiles of Austin-1 and
476 Maitland North-1 were correlated to the interglacials in the LR2004 curve (Lisiecki and
477 Raymo, 2005) and an age-depth profile constructed. The wetter and drier phases of northwest
478 Australia climate are indicated (Kawamura et., 2006). The gamma plots in black are 3 point
479 running point averages of the original (yellow) values in Maitland North-1 and Austin and a
480 30 point running average of the data in Angel-4. All gamma values (in APAI units) are
481 adjusted for well diameter.

482
483 Figure 6. A photomicrograph (in plain polarised light) of ooids in a calcarenite 6.5 m below present
484 sea bed in core BHC4 of the Angel Field (Figure 5). The ooid to the left of the figure is 2
485 mm in diameter.

486
487 Figure 7. **a.** and **b.** gamma profiles (in depth) of Matiland North-1 and Austin-1 showing ooids and
488 reef occurrence with ages are from Gallagher et al. (2009). **c.** and **d.** are the gamma profiles
489 of these two wells plotted (in age). Intervals of increased clay input (gamma peaks) are
490 interpreted to reflect relatively stronger monsoonal intensity. We also show the age of

known and predicted ooid occurrence and interpreted reef building phases. e. Data from Maitland North-1 and Austin-1 from Figure 5 (red box) are expanded to show possible correlations >0.3 Ma to 1.0 Ma to interglacial isotopic maxima in the LR2004 stack (Lisiecki and Raymo, 2005).

Figure 8. A correlation of the gamma wireline log data for wells on the Northwest Shelf, depths in metres below sea surface. The location of these wells is on Figure 2. The age data (green values in Ma) for Goodwyn-6, Tidepole-1, Wilcox-2, Austin-1 and Maitland North-1 (Mait N-1) are in Table 1. The top of Bare Formation approximates the top of the Miocene. The colored lines (ages in Ma) are gamma tie points. The gamma plots (in black) are 30 point running point averages of the original (gray) values. All gamma values are adjusted for well diameter.

Figure 9. A summary of the conditions leading to ooids and reef expansion on the Northwest Shelf correlated to the LR2004 stack (Lisiecki and Raymo, 2005).

Figure 10. Northwest Shelf reef initiation and global reef development. The pattern of reef expansion and contraction (in blue) follows the the glacio-eustatic cycles where reef expansion is interpreted to have happened in the transgressive phases of the interglacials and reef contraction in the glacial periods. Age estimates for the GBR are from Alexander et al. (2001) (1) and Dubois et al. (2009) (2); New Caledonia Barrier reefs, Montaggioni et al. (2011) (3); Ryukyu Reefs, Yamamoto et al. (2006) (5) and Sakai and Jige (2006) (6); Belize Barrier Reef, Gischler et al. (2010) (7) and Droxler and Jorry (2013) (8). The Mean Sea Level curve is from Rohling et al. (2009) (black curve) and Miller et al. (2011) (red curve). The ages of the transition from carbonate or siliclastic ramp facies to reef development is adapted from Montaggioni et al. (2011).

	Depth (m)	Age (Ma)	TWT	Depth (m)	Age (Ma)	TWT
1						
2	Austin-1 (A-1)	20.294°S	115.459°E	Maitland-1 (M1)	20.561°S	115.176°E
3	97.50	0.16		129.1	0.49	0.160
4	127.50	0.33		159.1	1.18	0.243
5	187.50	0.66		189.1	1.39	0.269
6	217.50	0.82		249.1	1.60	0.293
7	247.50	0.99				
8	277.50	1.15				
9				Matiland North-1 (MN1)	20.548°S	115.175°E
10	307.50	1.32		126.9	0.50	0.160
11	337.50	1.39		156.9	0.74	0.185
12						
13	Goodwyn 6 (G6)	19.722°S	115.854°E	186.9	0.97	0.210
14	537.50	1.46		246.9	1.44	0.260
15	577.50	2.63		296.9	1.83	0.302
16	597.50	3.21		326.9	2.07	0.327
17	617.50	3.79				
18	637.50	4.08		Tidepole-1	19.767°S	115.886°E
19	657.50	4.43		480.00	***3.13	0.500
20	677.50	4.72				
21	697.50	5.08				
22				Tryal Rocks-1 (TR1)	20.412°S	115.154°E
23	Fisher-1 (F1)	19.722°S	115.854°E	303.28	1.28	0.254
24	412	1.53	0.389	318.52	1.38	0.266
25	423	1.58	0.398	333.76	1.48	0.279
26	434	1.64	0.406	349.00	1.57	0.292
27	456	1.74	0.430	364.24	1.67	0.304
28	470	1.81	0.438	379.48	1.77	0.314
29	478	1.84	0.443	394.72	1.87	0.325
30	494	*1.92	0.454	409.96	1.97	0.335
31	517	2.06	0.486			
32				West Tryal Rocks-1 (WTR)	20.228°S	115.036°E
33	540	2.19	0.502	406.3	0.71	0.499
34	557	2.29	0.504	467.26	0.87	0.546
35	580	2.43	0.521	528.22	1.03	0.609
36	596	2.53	0.530	595.28	1.21	0.660
37	616	2.64	0.552	625.76	1.29	0.684
38	642	2.8	0.566	686.72	1.45	0.731
39	661	2.91	0.580	747.68	1.61	0.777
40	684	3.05	0.595	808.64	1.77	0.818
41	713	3.22	0.616	869.6	2.52	0.858
42	740	3.38	0.640	930.56	3.05	0.899
43	759	3.49	0.650			
44	792	3.69	0.673			
45	819	3.85	0.690	Wilcox-2 (W2)	19.994°S	115.509°E
46	842	3.98	0.706	430.00	#1.88	0.500
47	860	4.09	0.720			
48	877	4.19	0.734			
49	887	4.25	0.742			
50	898	4.32	0.743			
51	912	**4.4	0.755			
52	922	4.6	0.762			

Table 1

519 Table 1. The age/depth data for wells on the Northwest Shelf. Age data from Austin-1, Goodwyn-
520 2, Maitland-1, Maistland North-1, Tryal Rocks-1 and West Tryal Rocks-1 are adapted from
521 2 Gallagher et al. (2009) minus kb (kelly bushing). The velocity depth conversions (TWT =
522 4 Two Way Travel Time) are from well completion reports and can be sourced from
523 5 Geoscience Australia (<http://dbforms.ga.gov.au/www/npm.well.search>). *The first
524 7 appearance datum of *Globorotalia truncatulinoides* is at 494 m in the sidewall cores of
525 9 Fisher-1, this species first occurs at 1.92 Ma (Wade et al., 2011). **The first occurrence of
526 11 *Asterorotalia* spp. is at 920 m in Fisher-1, this taxon first occurs in the Northwest Shelf at
527 13 ~4.4Ma (Gallagher et al., 2009). ***The top of *Dentoglobigerina altispira* is at 480 m in
528 15 Tidepole-1, this taxon last occurs at 3.13 Ma (Wade et al., 2011). #The last occurrence of
529 17 *Globigerinoides fistulosus* is at 430m in Wilcox-2. This species last appears at 1.88 Ma
530 19 (Wade et al., 2011).

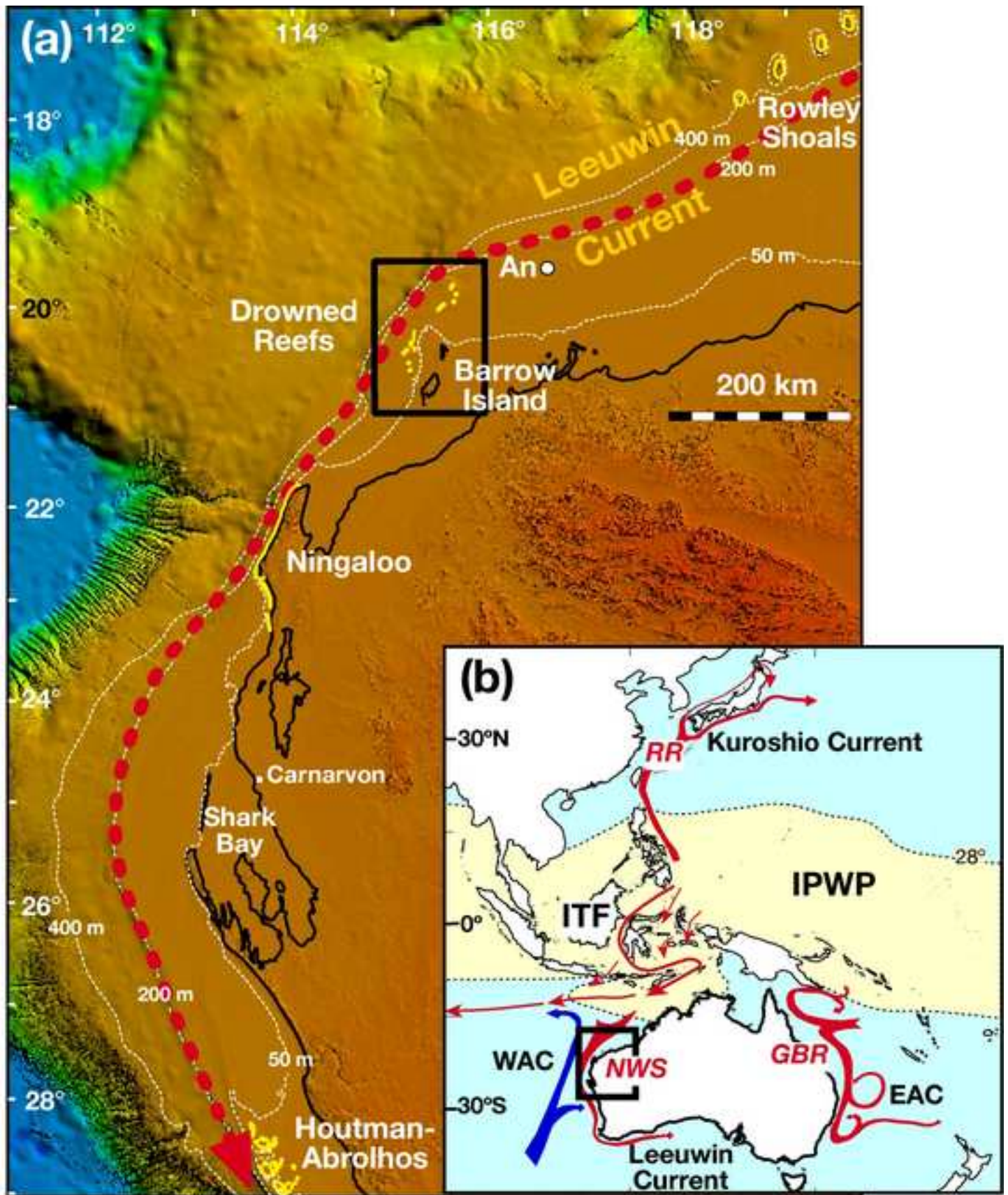


Figure 1

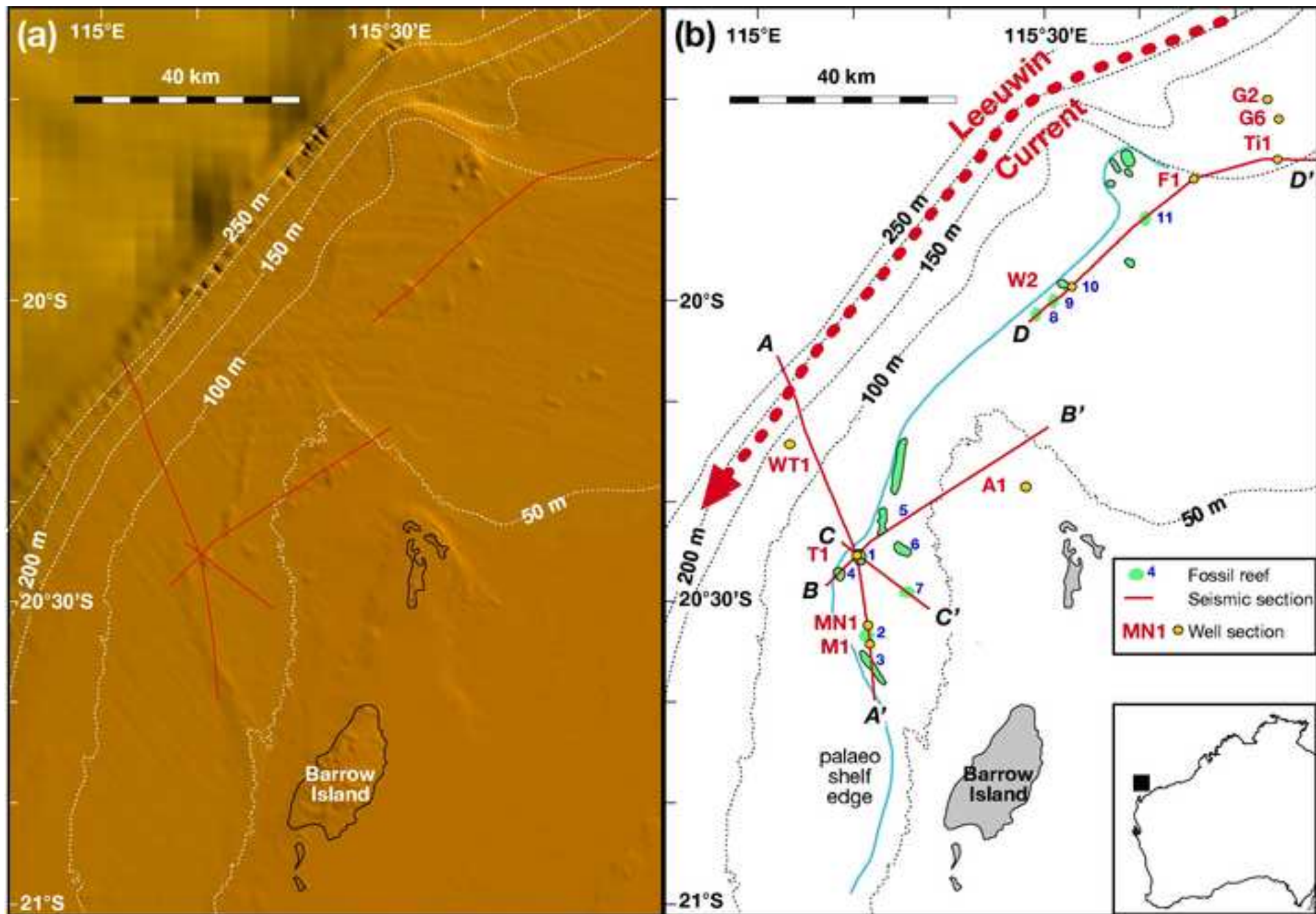


Figure 2

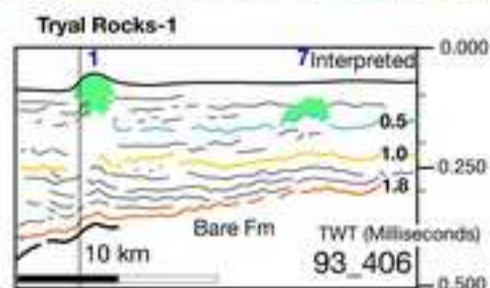
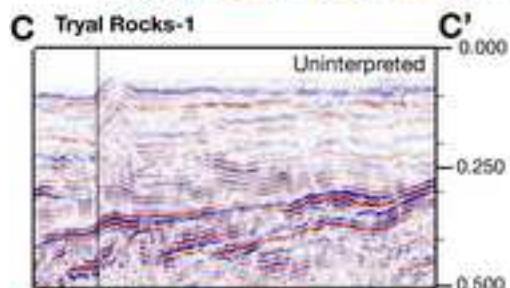
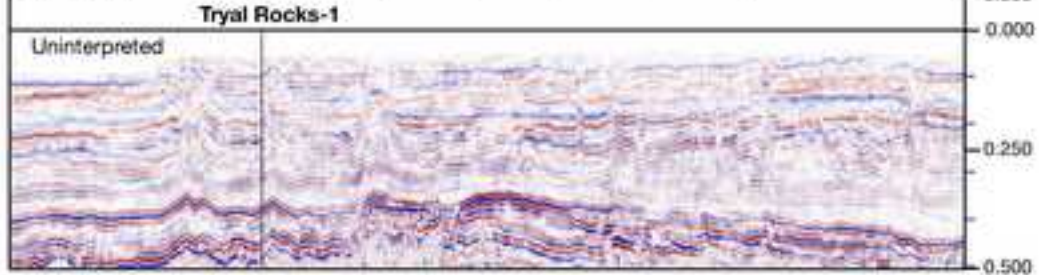
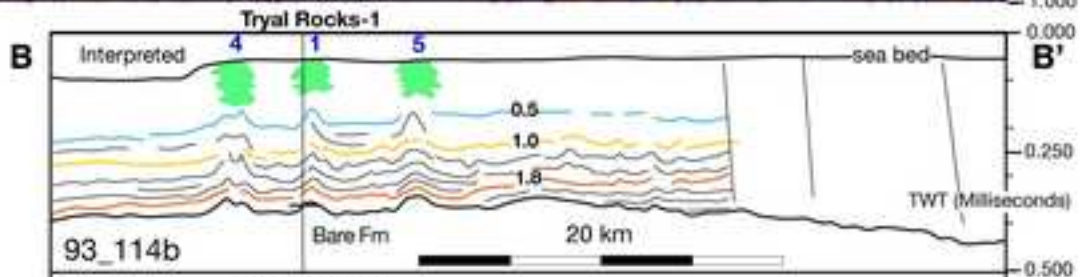
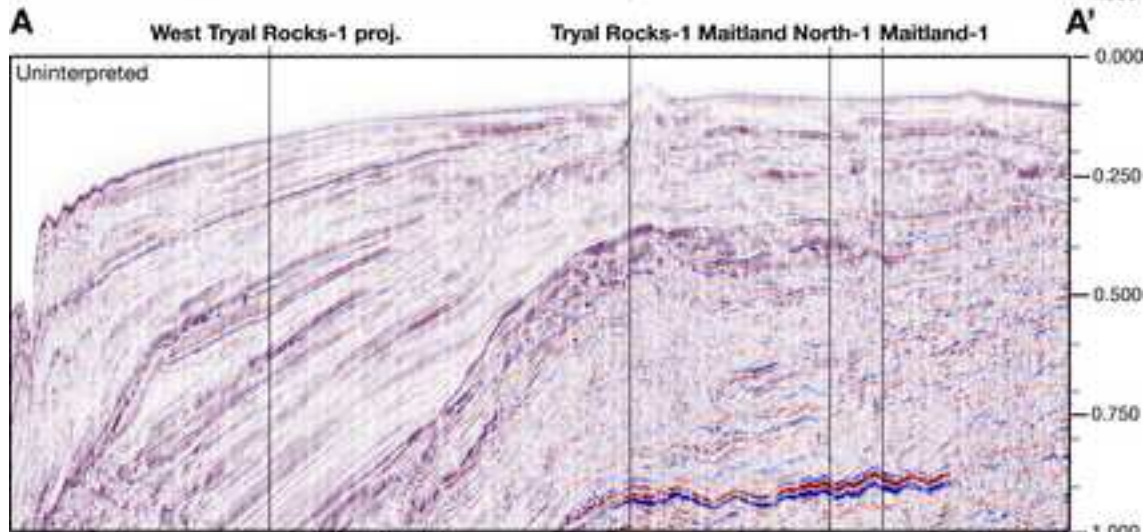
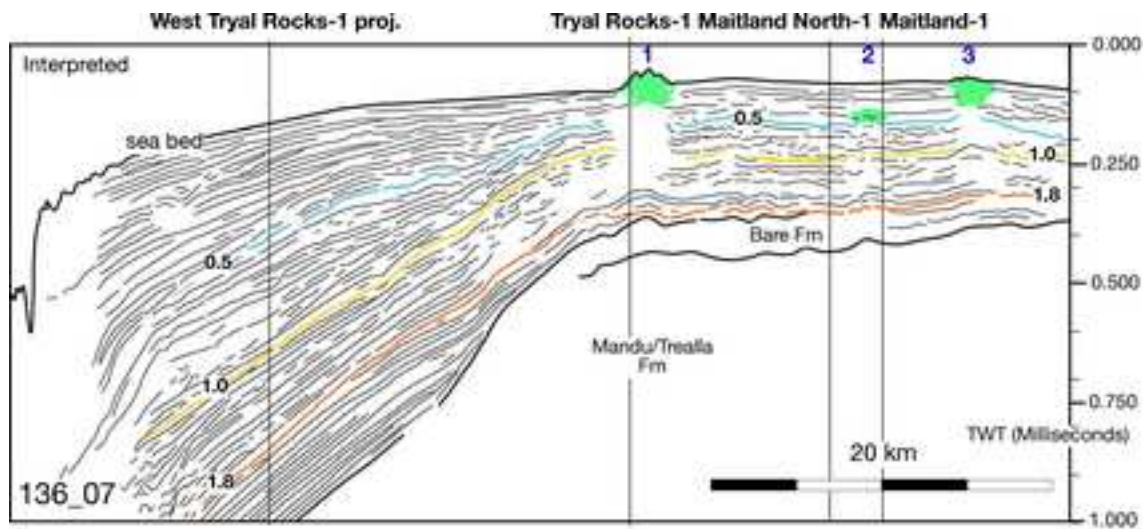


Figure 3

Figure

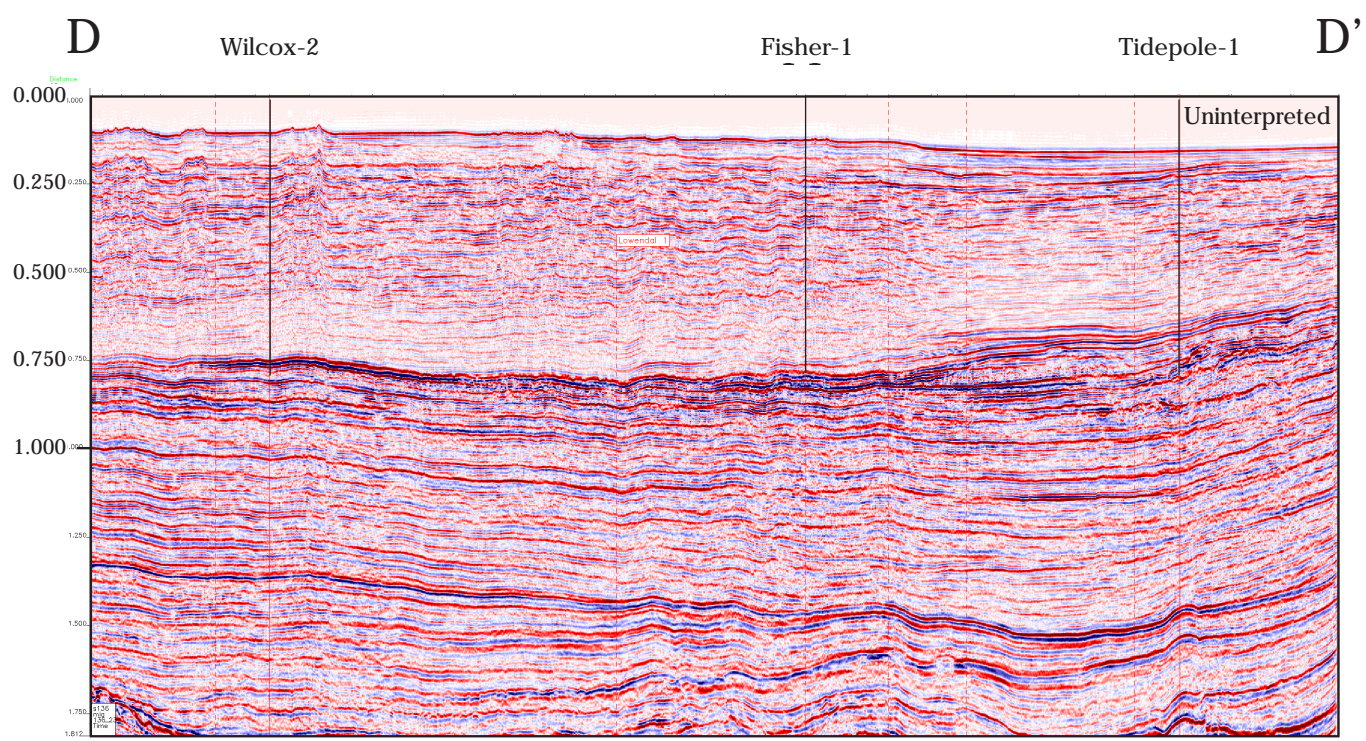
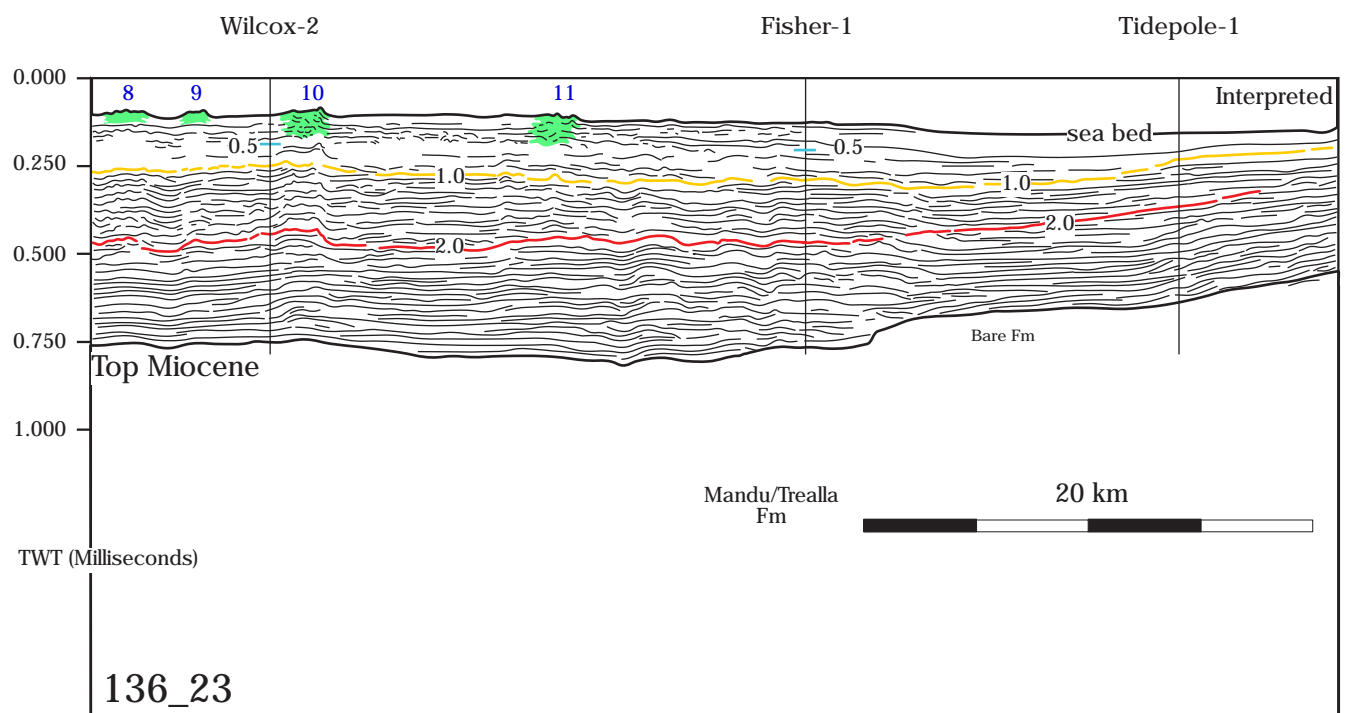


Figure 4

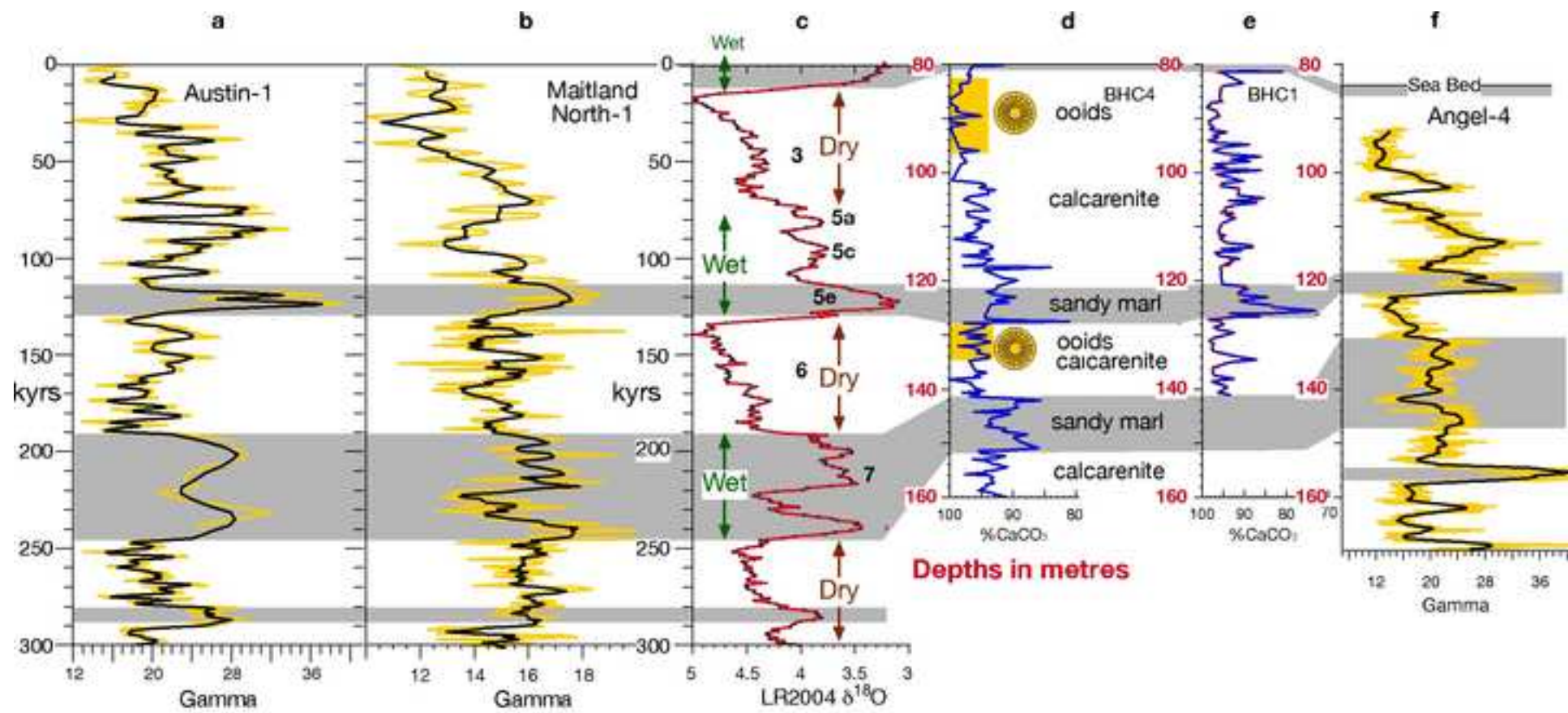


Figure 5

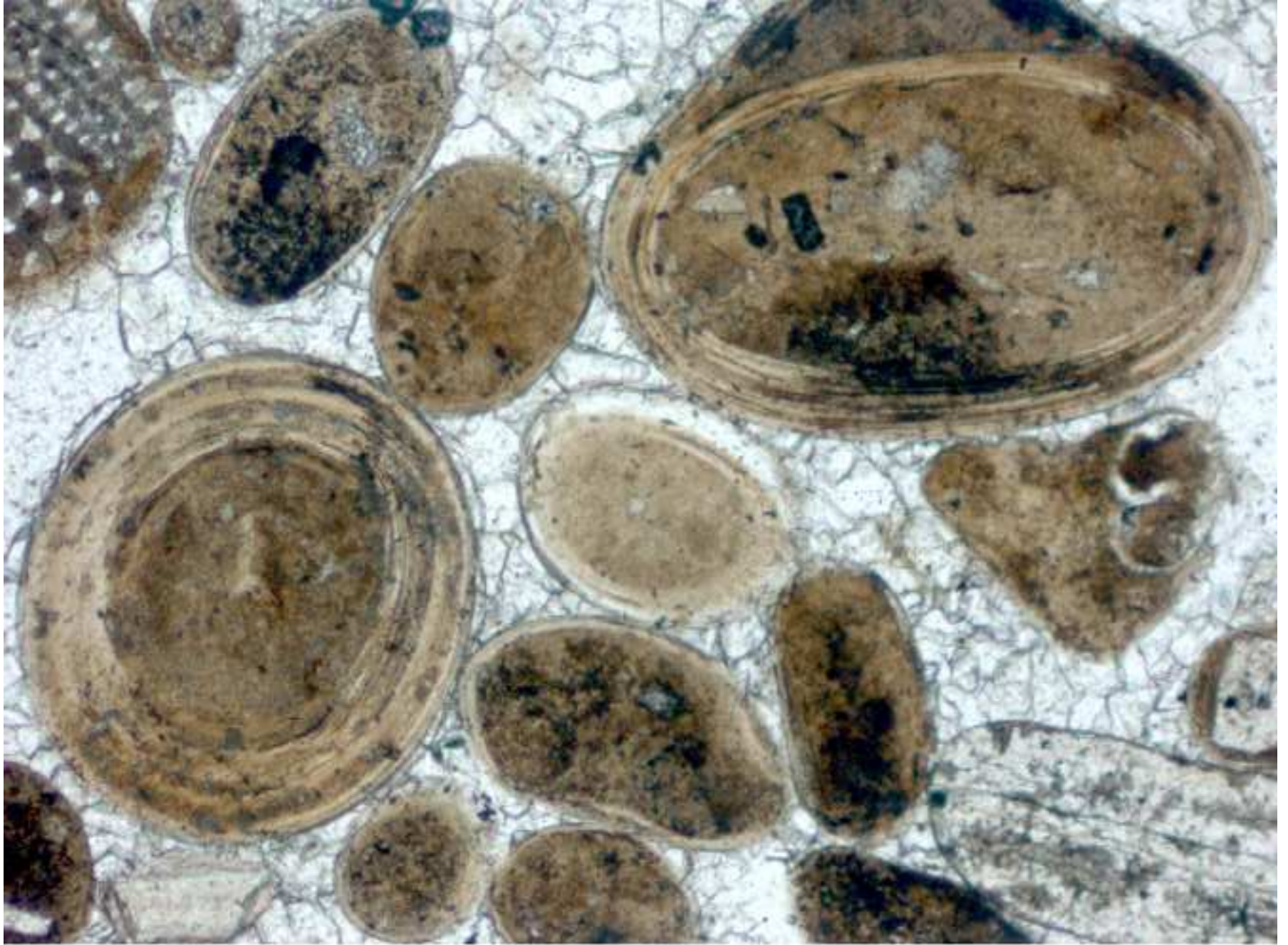


Figure 6

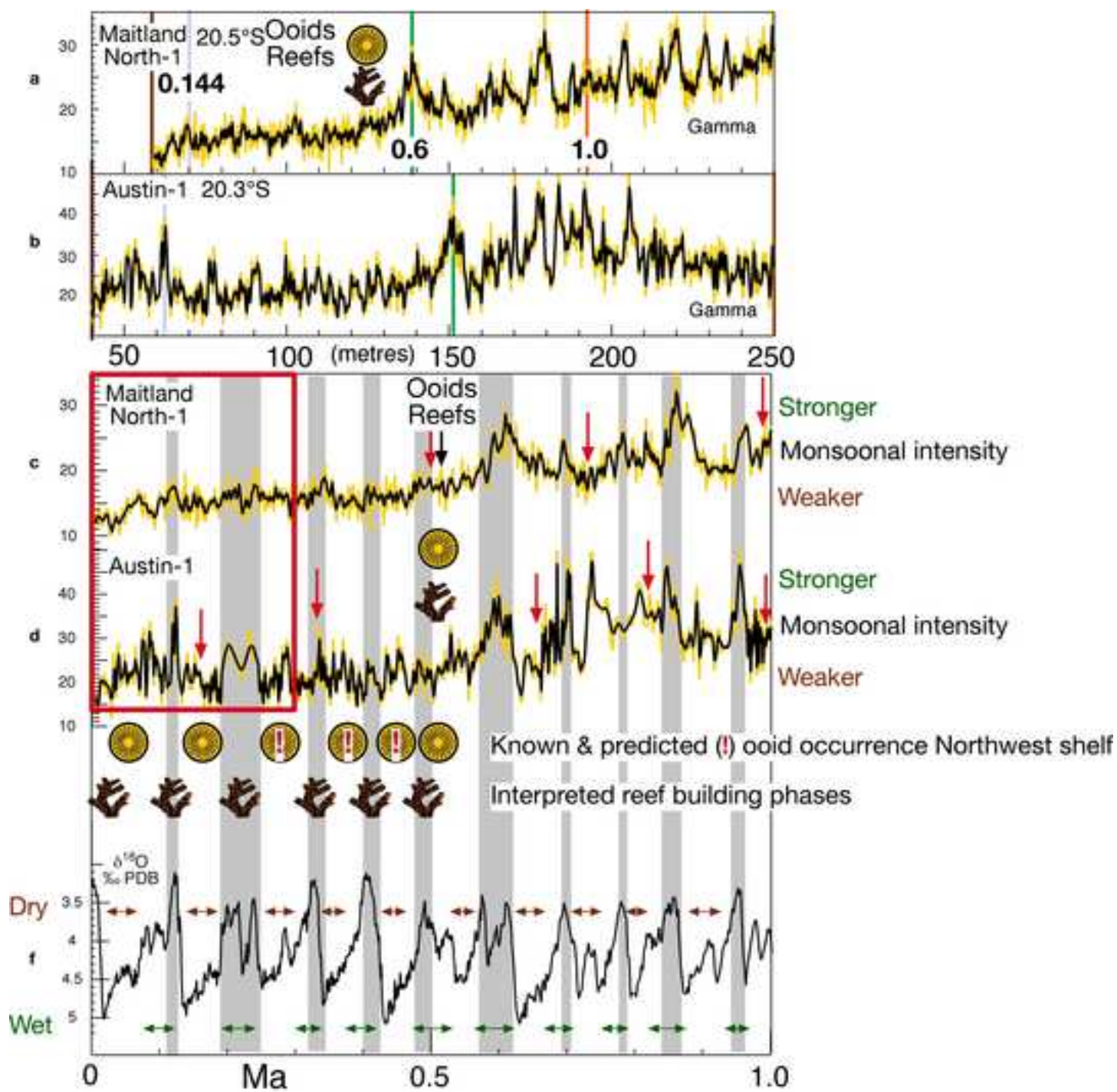


Figure 7

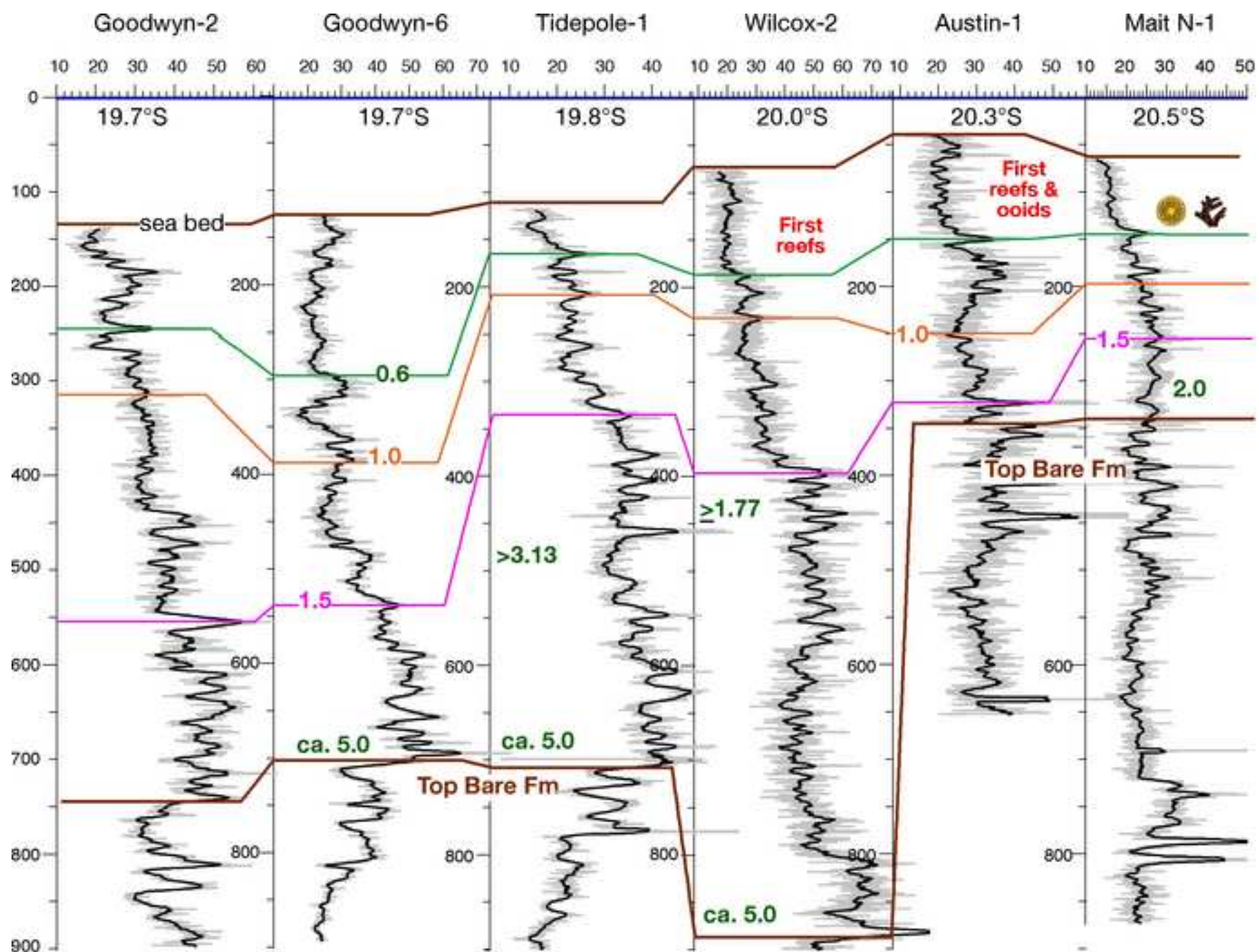


Figure 8

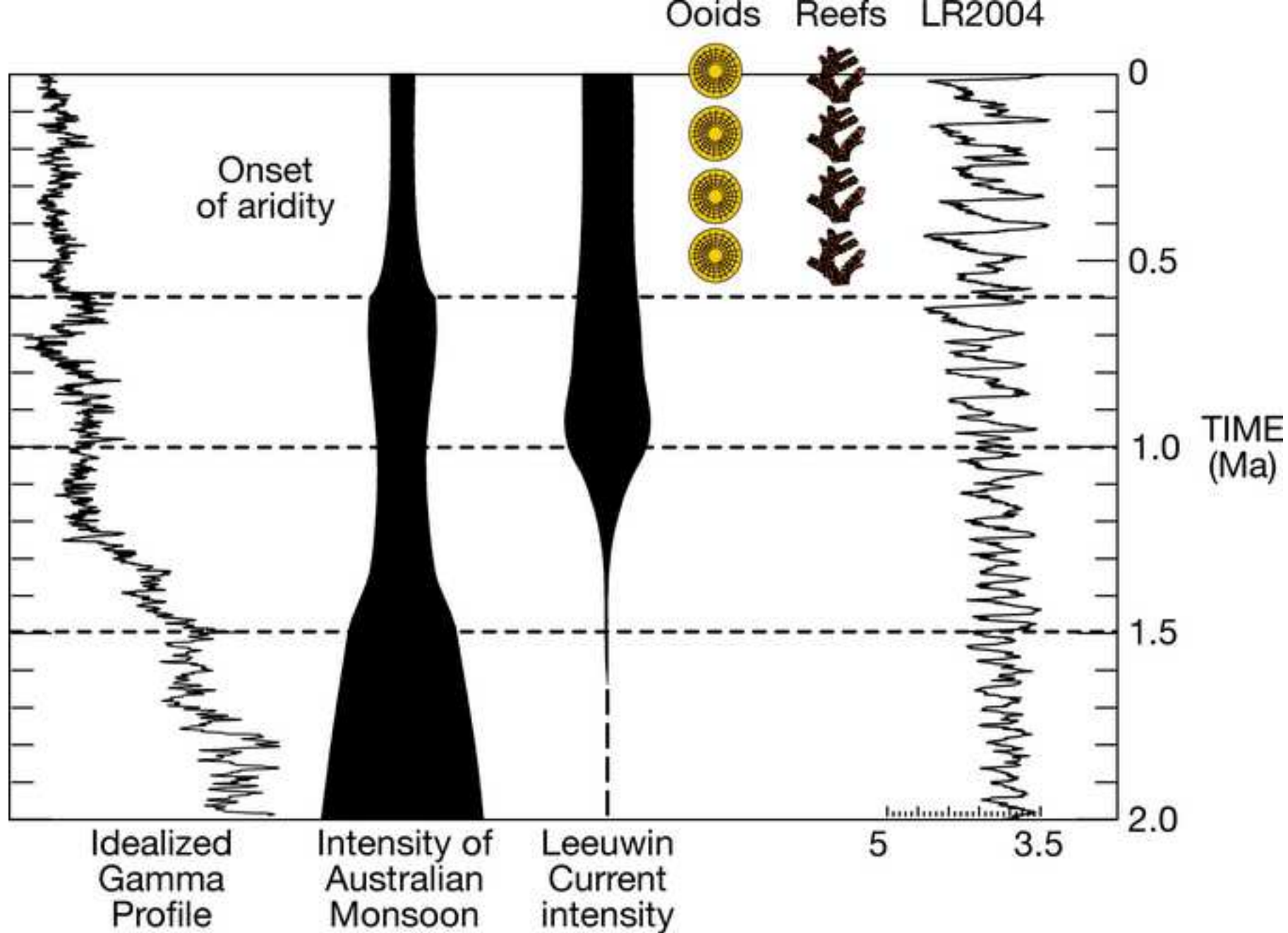


Figure 9

