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

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

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Abstract

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

1. Introduction

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

2. Methods

We have identified a series of previously unidentified fossil reefs within the carbonate dominated Neogene Delambre Formation (Wallace et al., 2003) in seismic data from the Northwest Shelf of Australia (19°S to 21°S, Figures 2 to 4). Reefs in the Delambre Formation can be identified by the presence of: bathymetric highs and irregularities on the sea floor; lenticular masses containing no reflectors; and strong velocity 'pull-up' structures beneath lenticular masses (cf. Ryan et al., 2009; Rosleff-Soerensen et al., 2012). To constrain the age and environmental setting of these reefs in the Delambre Formation we have used a combination of: biostratigraphic data from cuttings and sidewall cores (Gallagher et al., 2009), seismic stratigraphic, core and wireline log data. We analysed two continuously cored engineering bores (BHC4 and BHC1) near the Angel Field (Figure 1) in water depths of around 80 m (Figure 5). Facies, %$CaCO_3$ and wireline gamma log data are comparable to the LR2004 oxygen isotope record (Lisiecki and Raymo, 2005). For example the lower carbonate marly facies (with relatively high gamma response) were deposited during interglacial highstands and the high carbonate grainstone (with ooids, Figure 6) were deposited as sea level fell to glacial conditions. Furthermore, the wireline log data for Maitland North-1 and Austin-1 (Figure 5 and 7) also show a similar variability. Given this correlation, we have calibrated the wireline log data for Maitland North-1 and Austin-1 using biostratigraphic data (Gallagher et al., 2009) to constrain the age and climate context of the Pleistocene strata of the Delambre Formation (Figure 5 and 7). Additional wireline log data and biostratigraphic data (Table 1) from other wells (Figure 8) in the region are used to extend this record to the base of the Pliocene.

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 the Australian summer monsoon, which delivers substantial precipitation to the northern part of the continent in the Austral summer (Herold et al., 2011; Suppiah, 1992). The Australian monsoon is interpreted to be broadly controlled by global glacial–interglacial variations (Wyrwoll and Miller, 2001). Strong variations in Australian monsoonal strength between glacial and interglacial periods (paced by orbital eccentricity and precession) have been documented over the last 460 kyrs from 13°S off Northwest Australia (Kawamura et al., 2006), with stronger monsoonal (wet) conditions prevailing during interglacial periods and a weakened monsoon (dry) during glacials (Figure 5 and 7). Significant fluvial runoff and megalake expansion across northern and central Australia (Hesse et al., 2004) occurred during interglacials over the last 300 kyrs due to an enhanced Australian Monsoon. Conversely, reduced precipitation off the Northwest Shelf (at 23°S) (van der Kaars et al., 2006) and megalake contraction typified glacial conditions (Magee et al., 2004) associated with decreased monsoonal activity. We interpret the presence of increased siliciclastics (gamma peaks) on the Northwest Shelf to be related to increased precipitation and terrestrial siliciclastic runoff across the shelf during interglacial periods (due to an enhanced Australian Monsoon). The decrease in terrestrial input in the glacials was likely to have been due to increasingly arid conditions (reduced monsoon) starving the shelf of siliciclastics. Similar chronologically calibrated gamma wireline log data have been used to interpret Plio-Pleistocene climate records for ODP (Ocean Drilling Program) Site 119 (Carter and Gammon, 2004) and the Japan Sea (deMenocal et al., 1992). If the gamma log and sedimentation model is applied to the Plio-Pleistocene strata of the Northwest Shelf, the upward decrease in gamma values (Figure 5, 7 and 8) may be interpreted to reflect an upward increase in aridity that might be related to upward decreasing Australian Monsoon influence from the Pliocene to the Early Pleistocene. This aridity has two phases: one from ~1.5 Ma to ~1 Ma punctuated by a 0.4 Ma period of high gamma (precipitation) variability followed by upward increasing aridity after 0.6 Ma (Figure 9).

4. Discussion

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

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

4.1 The Leeuwin Current

The distribution and timing of modern coral reef development off West Australia is intimately related to the Leeuwin Current (Kendrick et al., 1991). The Leeuwin Current (Figure 1) is the only south-flowing eastern boundary current in the southern hemisphere. Its past intensity is related to Indonesian Throughflow connectivity and Indo-Pacific Warm Pool history (Gallagher et al., 2009). The Leeuwin Current extends modern tropical coral reef development to 29°S - the Houtman-Abrolhos reefs (Collins et al., 1993; Figure 1) and the tropical/subtropical transition as far south as Rottnest Island at 33°S (Greenstein and Pandolfi, 2008). While the Late Pleistocene record and modern oceanography of the Leeuwin Current is well known (see Cresswell, 1991; Pearce, 2009 and references therein) the pre-late Pleistocene history of this current off the west coast of Australia is not well known (Kendrick et al., 1991; Wyroll et al., 2009). Kendrick et al. (1991) used mollusc assemblages in marine carbonate strata near Perth Western Australia, to suggest that the Leeuwin Current was inactive or weak in the Early Pleistocene and became more intense by the Middle Pleistocene. Biogeographic studies using foraminifera on the Northwest Shelf have shown that there was intermittent and restricted Indonesian Throughflow (and Leeuwin Current) from ~4 to 1.6 million years ago (Gallagher et al., 2009). Thereafter, the Leeuwin Current became more intense from 1 to 0.8 Ma after which it reached its modern state. It would therefore appear that based on the history of the Leeuwin Current alone, by 0.8 Ma, regional oceanic conditions should have been suitable for reef development. However, it wasn't until ~0.5 Ma that reefs and ooids appeared on the Northwest Shelf (south of 18°S), suggesting that some other factor influenced reef growth.

4.2 Carbonate supersaturation

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

4.3 Aridity

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

If the patterns in our gamma data reflect relative precipitation and runoff from the Australian continent through time across the Northwest Australian Shelf, then Australian Monsoon intensity may have decreased in two steps, with drier conditions after ~1.5 Ma followed by a switch to modern aridity and monsoonal conditions after ~0.6 Ma (Figure 5, 6 and 9). The first of these drying phases corresponds to the disappearance of megalakes and the onset of Early Pleistocene aridification in Southeast Australia (McLaren and Wallace, 2010; Sniderman et al., 2009). The upward increase in aridity after this time in Northwest Australia also coincides with the expansion of extensive sand dune deposits formed in central Australia ~ 1 Ma (Fujioka and Chappell, 2010). The final phase of aridification after ~0.6 Ma and decrease in monsoonal intensity on the Northwest Shelf correlates to the drying of Lake Lefroy in Southwest Australia (Zheng et al., 1998) and the switch from an oxide to carbonate dominated weathering regime in the southern half of Australia during the Middle Pleistocene (Pillans and Bourman, 2001). We suggest this final aridification phase and a strong Leeuwin Current facilitated the southerly expansion of tropical carbonates (reef and ooids) off the west coast of Australia during the Middle Pleistocene (Figure 9).

5. Pleistocene sea level variability and global reef expansion

Reef expansion on the Northwest Shelf followed the first (MIS 16 ~620,000 years ago) of the high amplitude glacio-eustatic cycles at the end the Mid Pleistocene Transition (MPT: Figure 10). The reefs may have been deposited during MIS 15 or 13. Elsewhere, in the Indo-Pacific reef expansion (the Great Barrier Reef, Ryukyu Reefs and New Caledonian Barrier Reef) is interpreted to have been related to a combination of the initiation of high amplitude sea level variability during the MPT in the period from 1 million to 400,000 years and tectonic subsidence variations (Montaggioni et al., 2011). In the southern Caribbean, the Belize barrier reef also initiated during the mid to late Brunhes (Gischler et al., 2010; Droxler and Jorry, 2013). Droxler and Jorry (2013) suggest flooding of Pleistocene lowstand tropical fluvial regions or carbonate palaeokarsts during the unique transgression in the lead up to the MIS 11 (400,000 years) interglacial facilitated global barrier reef expansion (Droxler et al., 2003). However, estimates for the age for reef expansion vary (Figure 10) and most initiate before MIS 11. For example, Ryukyu reef initiation occurred from 1.07 million to 800,000 years ago (Sakai and Jige, 2006; Yamamoto et al., 2006). Estimates for GBR initiation range from 400 to 670,000 years (Alexander et al., 2001; Braithwaite et al., 2004; Dubois et al., 2008). The modern Belize Barrier reef expanded in the period from MIS 15 to MIS 11 (620,000 to 400,000 years ago, Droxler and Jorry, 2013). While all of these estimates coincide with the onset of the largest glacio-eustatic cycles in the Pleistocene, we suggest regional factors also control the variation in reef expansion and propagation. The northerly extension of the modern Ryukyu Reefs is strongly controlled by the Kuroshio Current (Iryu et al., 2006), in the past the Ryukyu Reef front migrated to more southerly latitudes in glacial periods, and migrated north during interglacials. The Kuroshio Current reached its present latitudinal limit and intensity during Pliocene (after 3 Ma) due to an enhanced North Pacific Gyre. The gyre intensification was related to the onset of the Northern Hemisphere Ice Sheet and closure of the Isthmus of Panama (Gallagher et al., 2009). It is possible that North Pacific Gyre and Kuroshio Current intensified in a step-wise way as the magnitude of glacio-eustatic variability increased through the MPT leading to reef expansion by 800,000 year ago. In the Coral Sea average sea surface temperatures remained relatively constant and greater than 20°C over the last 1.6 million years (Russon et al., 2011) suggesting GBR and New Caledonia Barrier Reef expansion was not primarily controlled by this factor (Russon, 2011). However, glacial sea surface temperatures dropped below 18°C (Russon, 2011), the temperature limit for reef development (Kleypas et al., 1999), suggesting sea level variability was not the only influence affecting reef development in this area. Furthermore, Montaggioni et al. (2011) reviewed the role of climate change on reef development in the western Pacific and Caribbean and suggest its role is not clear, however, these authors conclude that climate conditions appear not to have been suitable for enhanced coral development during the early and middle Pleistocene.

6. Conclusions

A series of Pleistocene drowned reefs (south of 18°S) are described on the Northwest Shelf of Australia for the first time. Seismic and subsurface stratigraphic data suggest that these reefs initiated in the Middle Pleistocene ~0.5 Ma associated with the oldest oolites in the Indian Ocean. The expansion of reefs (the Great Barrier and Ryukyu Reefs) in the Indo-Pacific may have been related Indo-Pacific Warm Pool expansion during the Middle Pleistocene Transition. However, the majority of reefs expanded in the Indo-Pacific and the Caribbean following the onset of high amplitude glacio-eustatic cycles of the Middle Pleistocene Transition after 650,000 year ago. During this time it is postulated that luxuriant reefs advanced over large tracts of previously exposed ramp surfaces during flooding events leading to global reef expansion. However, other regional factors influence reef development and global reef diachroneity. Kuroshio Current intensity influences the Ryukyu Reef development and this current may have facilitated its early expansion (after 1 Ma). Sea surface temperatures during glacial phases may have limited reef development in the Coral Sea (the GBR and New Caledonia Barrier Reef). In addition, the regional setting of the Northwest Shelf is complicated by the degree of Indonesian Throughflow restriction which controls the relative intensity of warm south flowing Leeuwin Current, a current that controls the present reef distribution off western Australia. We suggest an increase in Leeuwin Current activity at ~1 Ma may have been followed by a reduction in Australian Monsoon intensity (and increased aridity) after 0.6 Ma leading to supersaturated conditions appropriate for reef expansion and ooid formation (Figure 9). Tropical carbonate deposition on the Northwest Shelf was also likely to have been influenced by the inception of the first high amplitude glacio-eustatic cycles during the Middle Pleistocene Transition, however, the relative intensity of Indonesian Throughflow, Indo-Pacific Warm Pool variability and continental aridity exerted a strong regional control on their evolution and expansion into higher latitudes.

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List of Figures

Figure 1. The location of the Northwest Shelf of Australia and it relationship to Indo-Pacific palaeoceanography (a) The bathymetry of the Northwest Shelf (NWS) from the Geoscience Australia: *Australian bathymetry and topography grid, June 2009* (http://www.ga.gov.au/meta/ANZCW0703013116.html#citeinfo). The path of the Leeuwin Current is shown along with the position of the nearest Recent reefs (the Houtman-Abrolhos, Ningaloo Reefs and Rowley Shoals) and the Drowned Reefs described in this paper (Box = Figure 2). The position of the Angel field (An) is indicated. (b) Inset map of the oceanography of the Indo-Pacific Warm Pool (IPWP). WAC = West Australian Current, ITF = Indonesian Throughflow, RR = Ryukyu Reefs and GBR = Great Barrier Reef. The 28°C isotherm is shown, the red currents are warm and the blue cold (Gallagher et al., 2009).

Figure 2. (a) The bathymetry of the Barrow Island region (for location see Figure 1), (b) A map of the drowned reefs of the Northwest Shelf of Australia (NWS). Wells used in stratigraphy: A1 = Austin-1, F1 = Fisher-1, G2/G6 = Goodwyn-2/6, M1 = Maitland-1, MN1 = Maitland North-1, T1 = Tryal Rocks-1, Ti1 = Tidepole-1, W2 = Wilcox-2 and WT1 = West Tryal Rocks-1. The reefs with the black outline have bathymetric expression, those without are in the subsurface and are interpreted from seismic data. The position of four interpreted seismic sections are indicated (Figure 3 and 4).

Figure 3. Seismic data from the Northwest Shelf. The 0.5 Ma (blue), 1.0 Ma (yellow) and 1.8 Ma (red) reflectors are indicated. The location of the drowned reefs (light green with blue numbers) and the seismic sections are shown on Figure 2. The age of the reflectors are based on the age/depth/TWT (Two Travel Time) well data in Table 1.

Figure 4. Seismic section D-D’ from the Northwest Shelf. The 0.5 Ma (blue), 1.0 Ma (yellow) and 2 Ma (red) reflectors are indicated. The location of the drowned reefs (light green with blue

numbers) and the seismic sections are shown on Figure 2. The age of the reflectors are based on the age/depth/TWT (Two Travel Time) well data in Table 1.

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

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

Figure 7. **a.** and **b.** gamma profiles (in depth) of Matiland North-1 and Austin-1 showing ooids and reef occurrence with ages are from Gallagher et al. (2009). **c.** and **d.** are the gamma profiles of these two wells plotted (in age). Intervals of increased clay input (gamma peaks) are 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 devlopment. 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
Austin-1 (A-1)	**20.294°S**	**115.459°E**	**Maitland-1 (M1)**	**20.561°S**	**115.176°E**
97.50	0.16		129.1	0.49	0.160
127.50	0.33		159.1	1.18	0.243
187.50	0.66		189.1	1.39	0.269
217.50	0.82		249.1	1.60	0.293
247.50	0.99				
277.50	1.15		**Matiland North-1 (MN1)**	**20.548°S**	**115.175°E**
307.50	1.32		126.9	0.50	0.160
337.50	1.39		156.9	0.74	0.185
Goodwyn 6 (G6)	**19.722°S**	**115.854°E**	186.9	0.97	0.210
537.50	1.46		246.9	1.44	0.260
577.50	2.63		296.9	1.83	0.302
597.50	3.21		326.9	2.07	0.327
617.50	3.79				
637.50	4.08		**Tidepole-1**	**19.767°S**	**115.886°E**
657.50	4.43		480.00	*****3.13**	0.500
677.50	4.72				
697.50	5.08		**Tryal Rocks-1 (TR1)**	**20.412°S**	**115.154°E**
Fisher-1 (F1)	**19.722°S**	**115.854°E**	303.28	1.28	0.254
412	1.53	0.389	318.52	1.38	0.266
423	1.58	0.398	333.76	1.48	0.279
434	1.64	0.406	349.00	1.57	0.292
456	1.74	0.430	364.24	1.67	0.304
470	1.81	0.438	379.48	1.77	0.314
478	1.84	0.443	394.72	1.87	0.325
494	***1.92**	0.454	409.96	1.97	0.335
517	2.06	0.486			
540	2.19	0.502	**West Tryal Rocks-1 (WTR)**	**20.228°S**	**115.036°E**
557	2.29	0.504	406.3	0.71	0.499
580	2.43	0.521	467.26	0.87	0.546
596	2.53	0.530	528.22	1.03	0.609
616	2.64	0.552	595.28	1.21	0.660
642	2.8	0.566	625.76	1.29	0.684
661	2.91	0.580	686.72	1.45	0.731
684	3.05	0.595	747.68	1.61	0.777
713	3.22	0.616	808.64	1.77	0.818
740	3.38	0.640	869.6	2.52	0.858
759	3.49	0.650	930.56	3.05	0.899
792	3.69	0.673			
819	3.85	0.690	**Wilcox-2 (W2)**	**19.994°S**	**115.509°E**
842	3.98	0.706	430.00	**#1.88**	0.500
860	4.09	0.720			
877	4.19	0.734			
887	4.25	0.742			
898	4.32	0.743			
912	****4.4**	0.755			
922	4.6	0.762			

Table 1

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

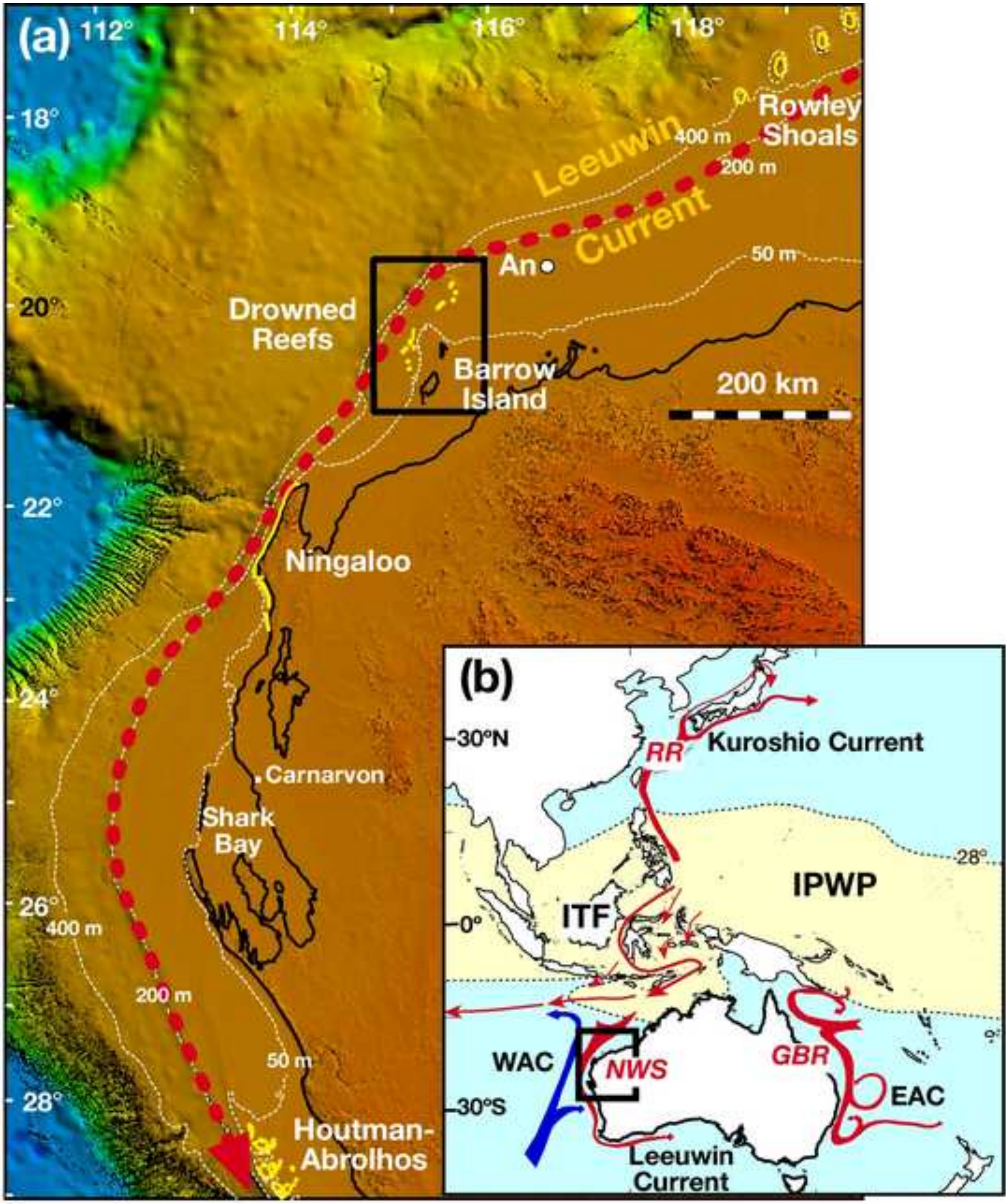

(a)
112°
114°
116°
118°
18°
20°
22°
24°
26°
28°
Rowley Shoals
Leeuwin Current
400 m
200 m
50 m
An
Drowned Reefs
Barrow Island
200 km
Ningaloo
Carnarvon
Shark Bay
400 m
200 m
50 m
Houtman-Abrolhos
(b)
30°N
RR
Kuroshio Current
28°
IPWP
ITF
0°
WAC
NWS
GBR
EAC
30°S
Leeuwin Current

Figure 1

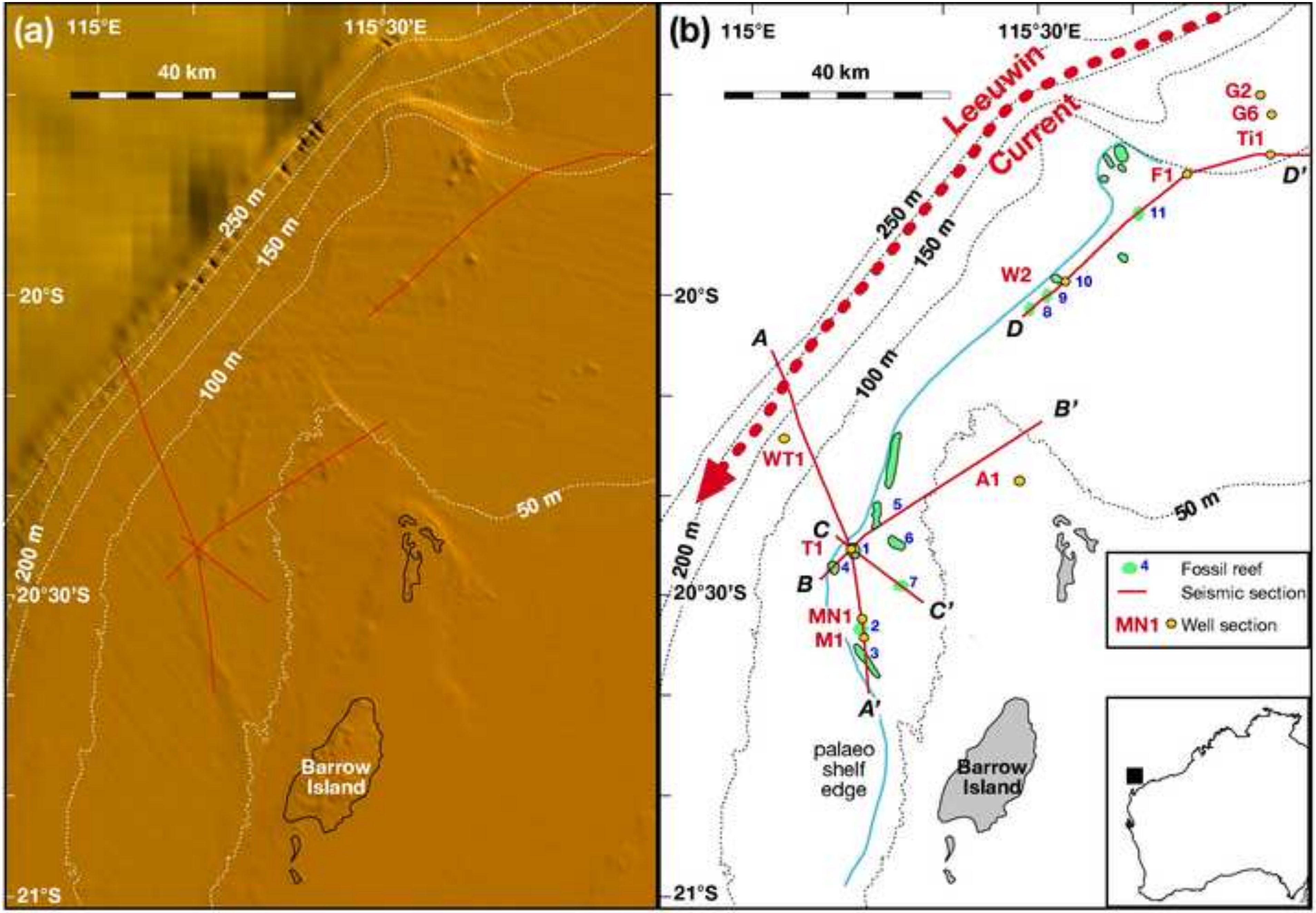

(a)
115°E
115°30'E
40 km
250 m
150 m
100 m
50 m
200 m
20°S
20°30'S
21°S
Barrow Island
(b)
115°E
115°30'E
40 km
Leeuwin Current
250 m
150 m
100 m
50 m
200 m
20°S
20°30'S
21°S
G2
G6
Ti1
F1
D'
11
W2
10
9
8
D
A
B'
WT1
A1
5
C
T1
1
6
4
B
7
C'
MN1
2
M1
3
A'
palaeo shelf edge
Barrow Island
4 Fossil reef
Seismic section
MN1 Well section

Figure 2

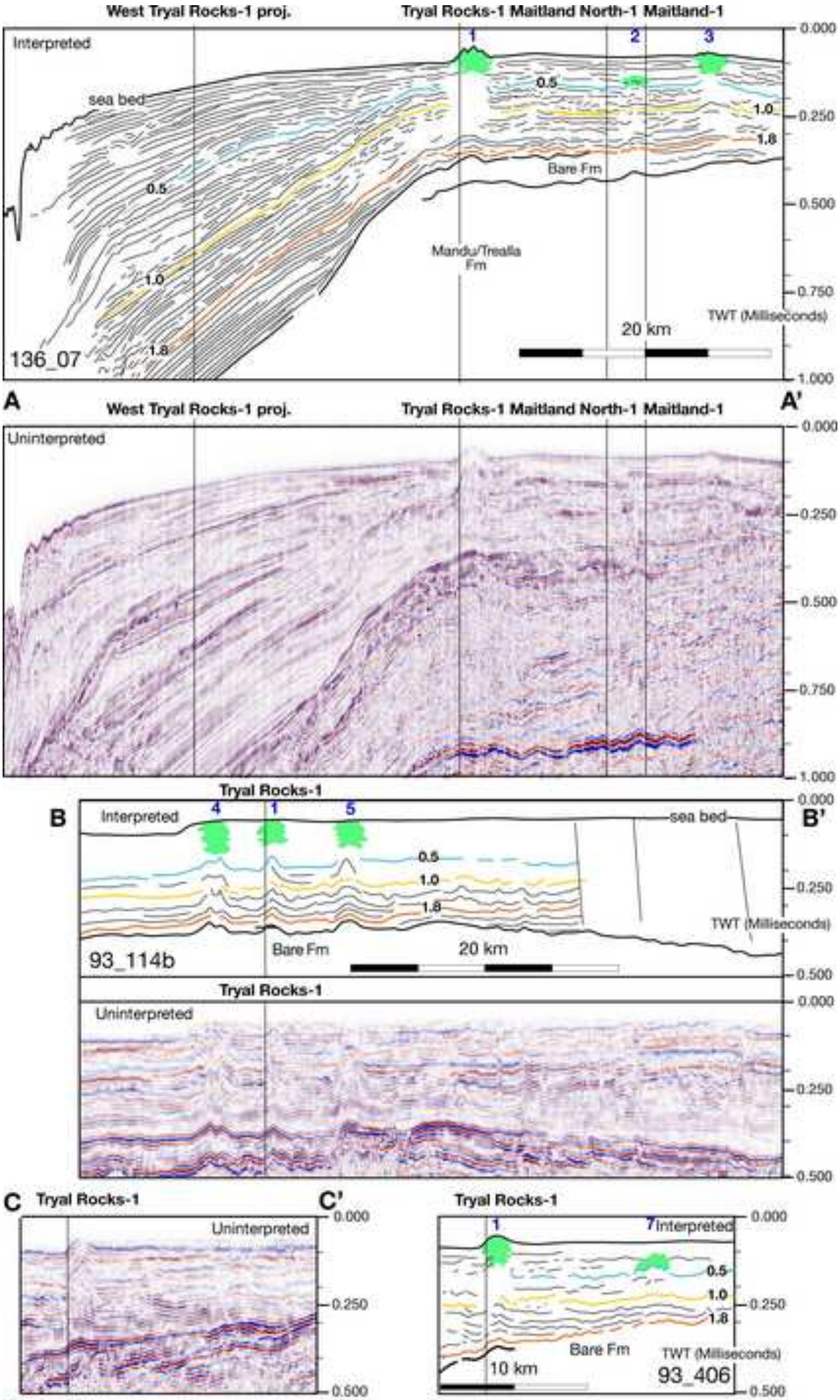

West Tryal Rocks-1 proj.
Tryal Rocks-1 Maitland North-1 Maitland-1
Interpreted
1
2
3
sea bed
0.5
1.0
1.8
Bare Fm
Mandu/Trealla Fm
20 km
TWT (Milliseconds)
136_07
0.000
0.250
0.500
0.750
1.000
A
A'
Uninterpreted
Tryal Rocks-1
B
B'
4
5
93_114b
C
C'
7
10 km
93_406

Figure 3

Figure

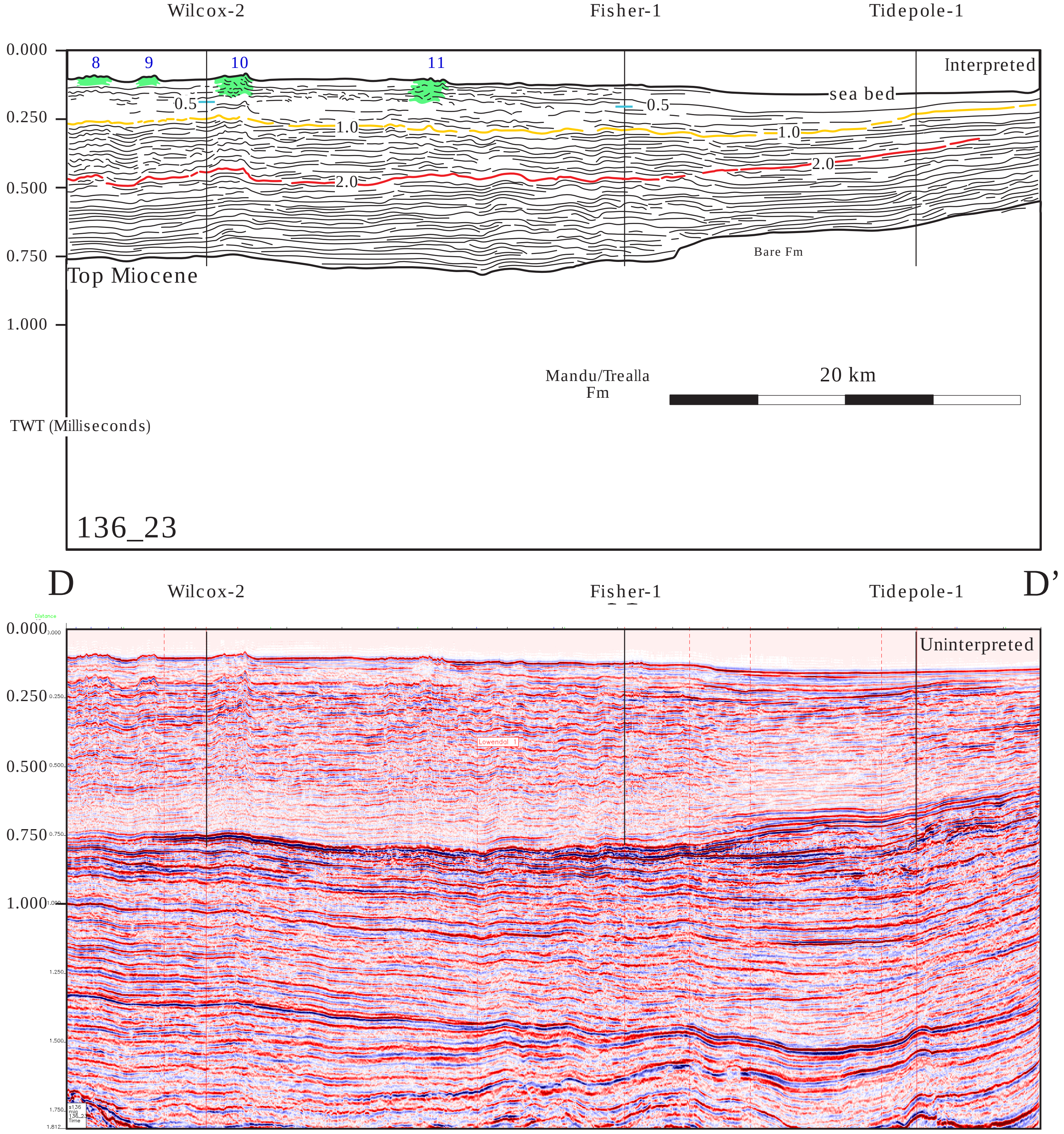


Figure 4

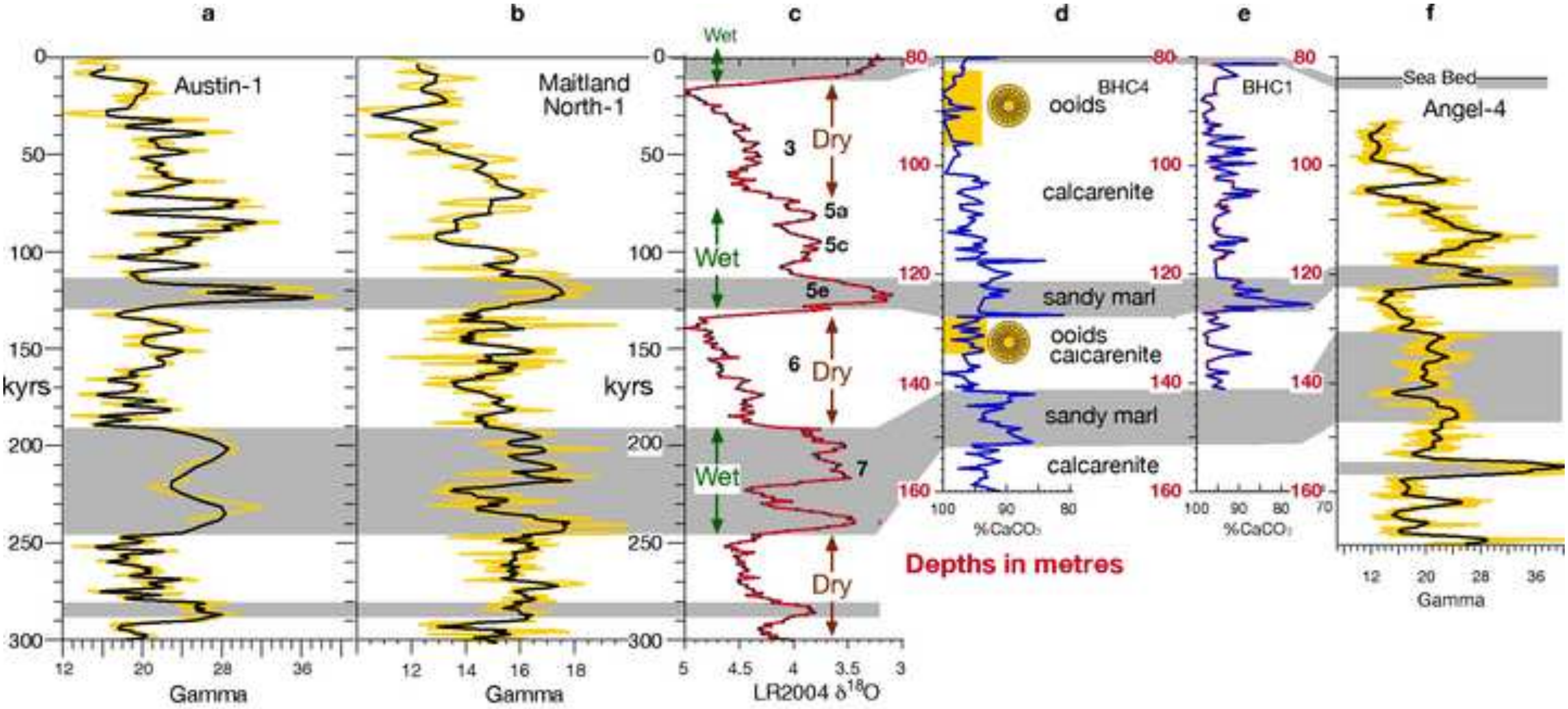

a
b
c
d
e
f
Austin-1
Maitland North-1
kyrs
Gamma
Wet
Dry
3
5a
5c
5e
6
7
LR2004 δ18O
BHC4
ooids
calcarenite
sandy marl
ooids calcarenite
sandy marl
calcarenite
%CaCO3
BHC1
Depths in metres
Sea Bed
Angel-4
Gamma

Figure 5

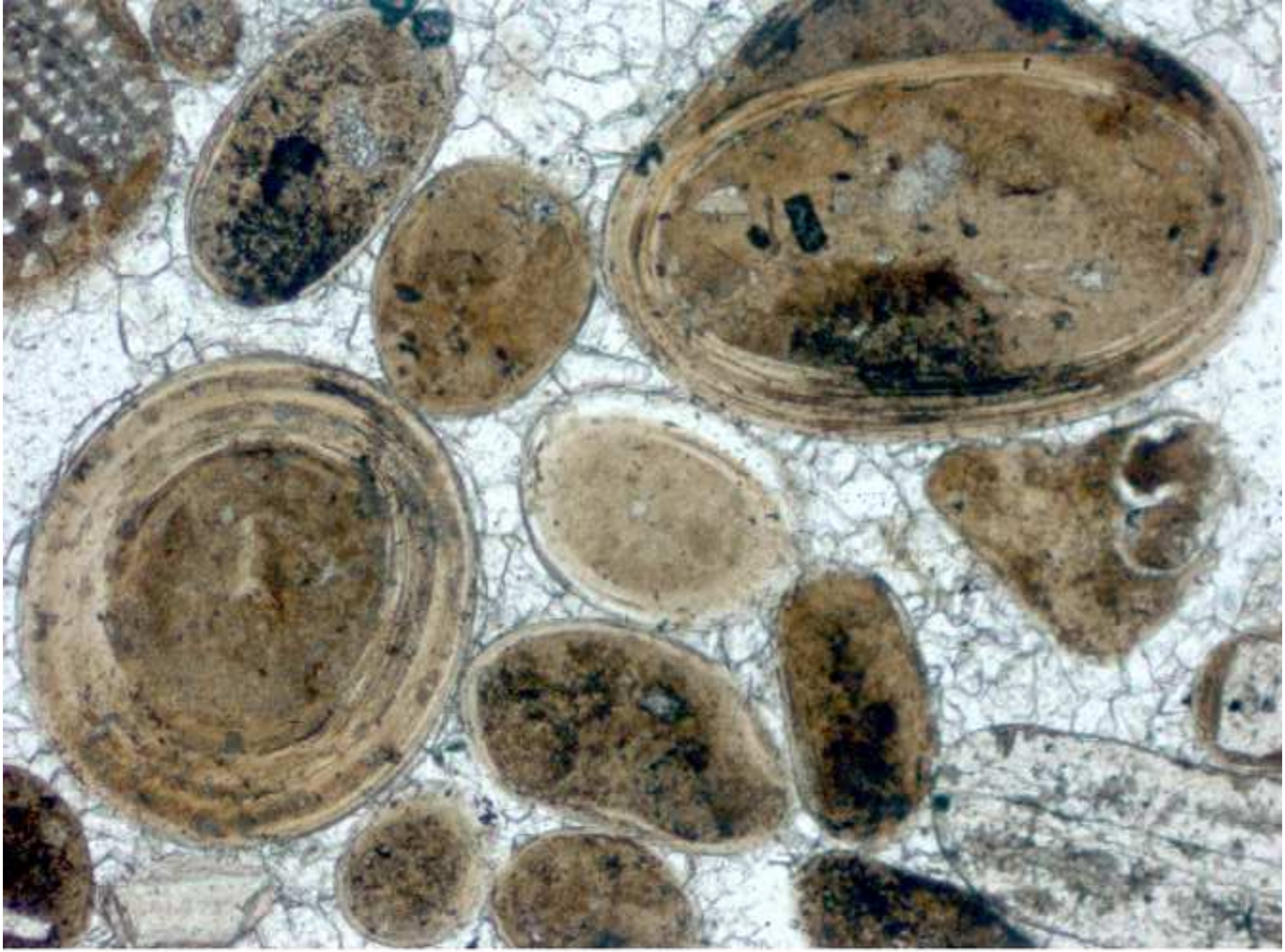


Figure 6

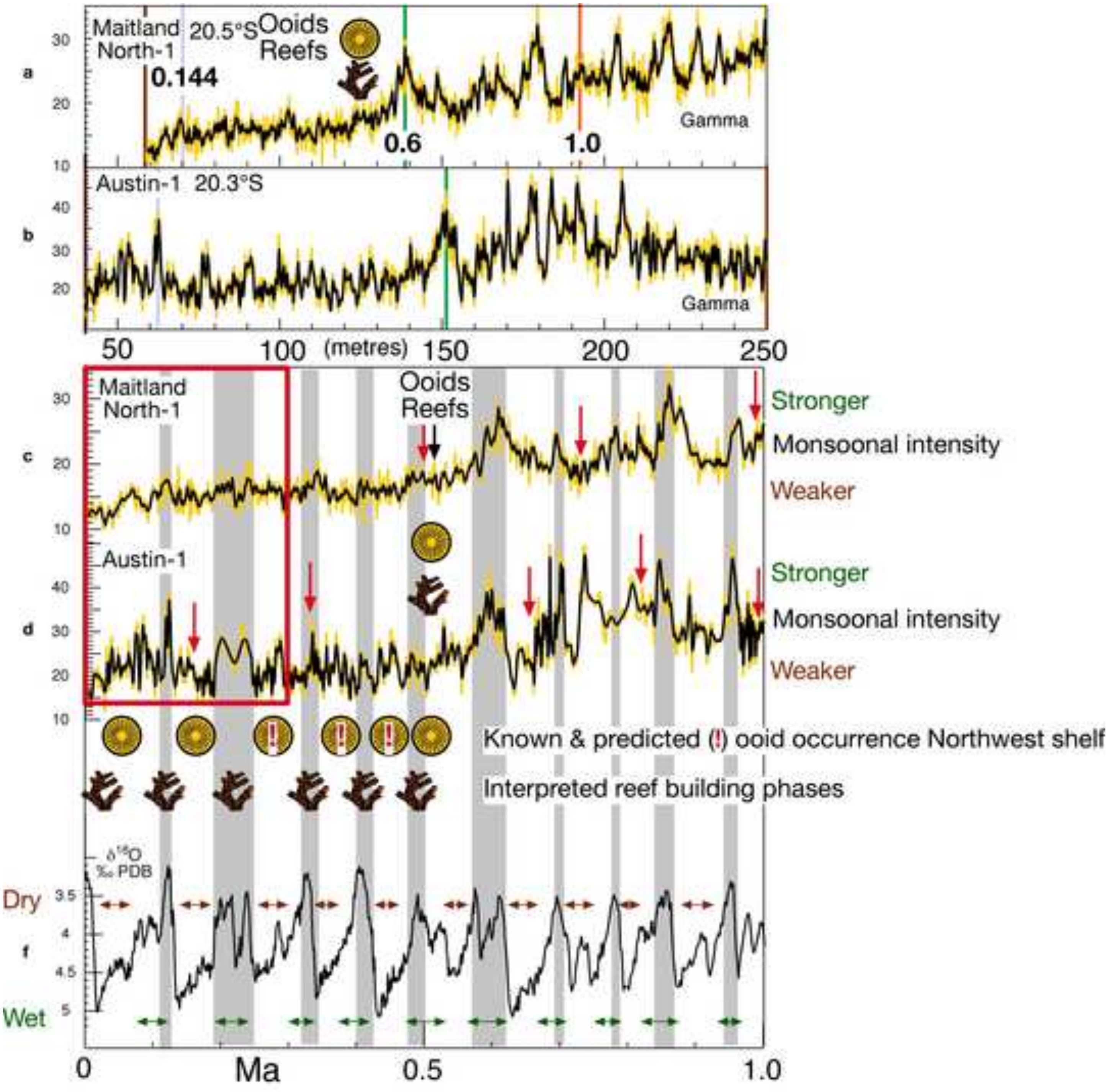

a
Maitland North-1 20.5°S
Ooids
Reefs
0.144
0.6
1.0
Gamma
30
20
10
b
Austin-1 20.3°S
40
30
20
Gamma
50
100
(metres)
150
200
250
c
Maitland North-1
Ooids
Reefs
Stronger
Monsoonal intensity
Weaker
30
20
10
d
Austin-1
40
30
20
10
Stronger
Monsoonal intensity
Weaker
Known & predicted (!) ooid occurrence Northwest shelf
Interpreted reef building phases
δ18O ‰ PDB
Dry
3.5
4
f
4.5
5
Wet
0
Ma
0.5
1.0

Figure 7

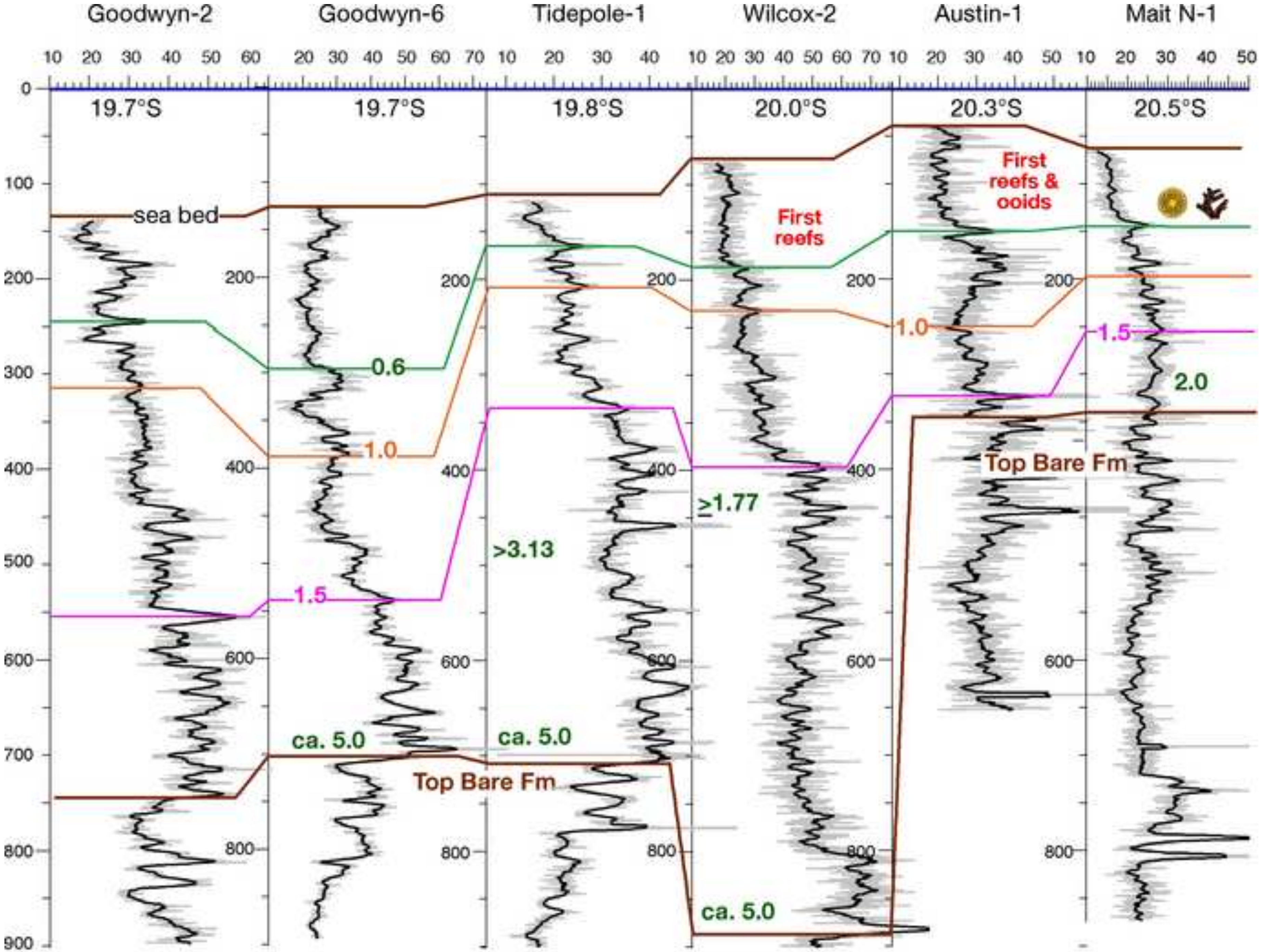

Goodwyn-2
Goodwyn-6
Tidepole-1
Wilcox-2
Austin-1
Mait N-1
19.7°S
19.7°S
19.8°S
20.0°S
20.3°S
20.5°S
sea bed
First reefs
First reefs & ooids
0.6
1.0
1.0
1.5
1.5
2.0
>3.13
≥1.77
ca. 5.0
ca. 5.0
ca. 5.0
Top Bare Fm
Top Bare Fm
0
100
200
300
400
500
600
700
800
900

Figure 8

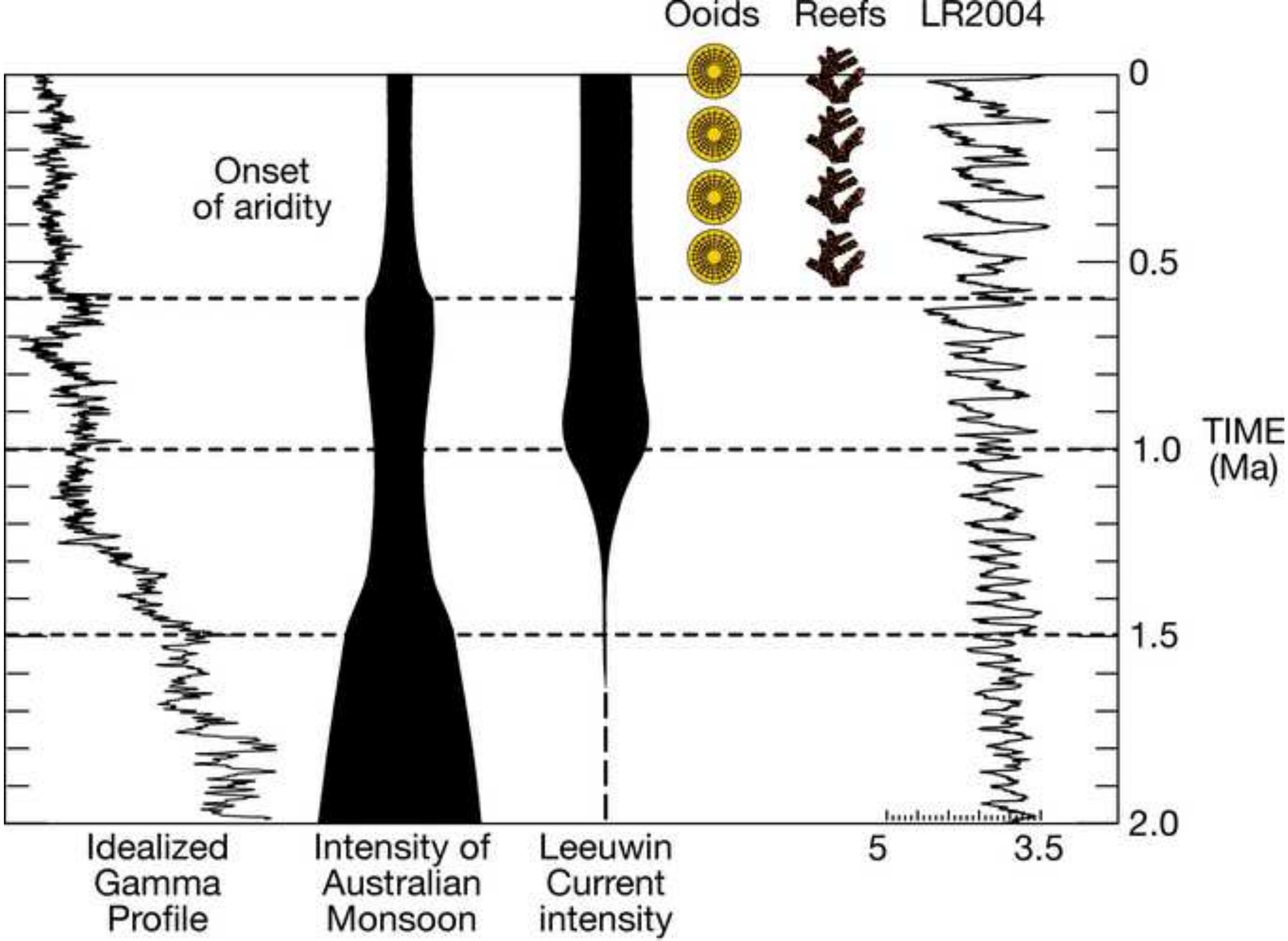
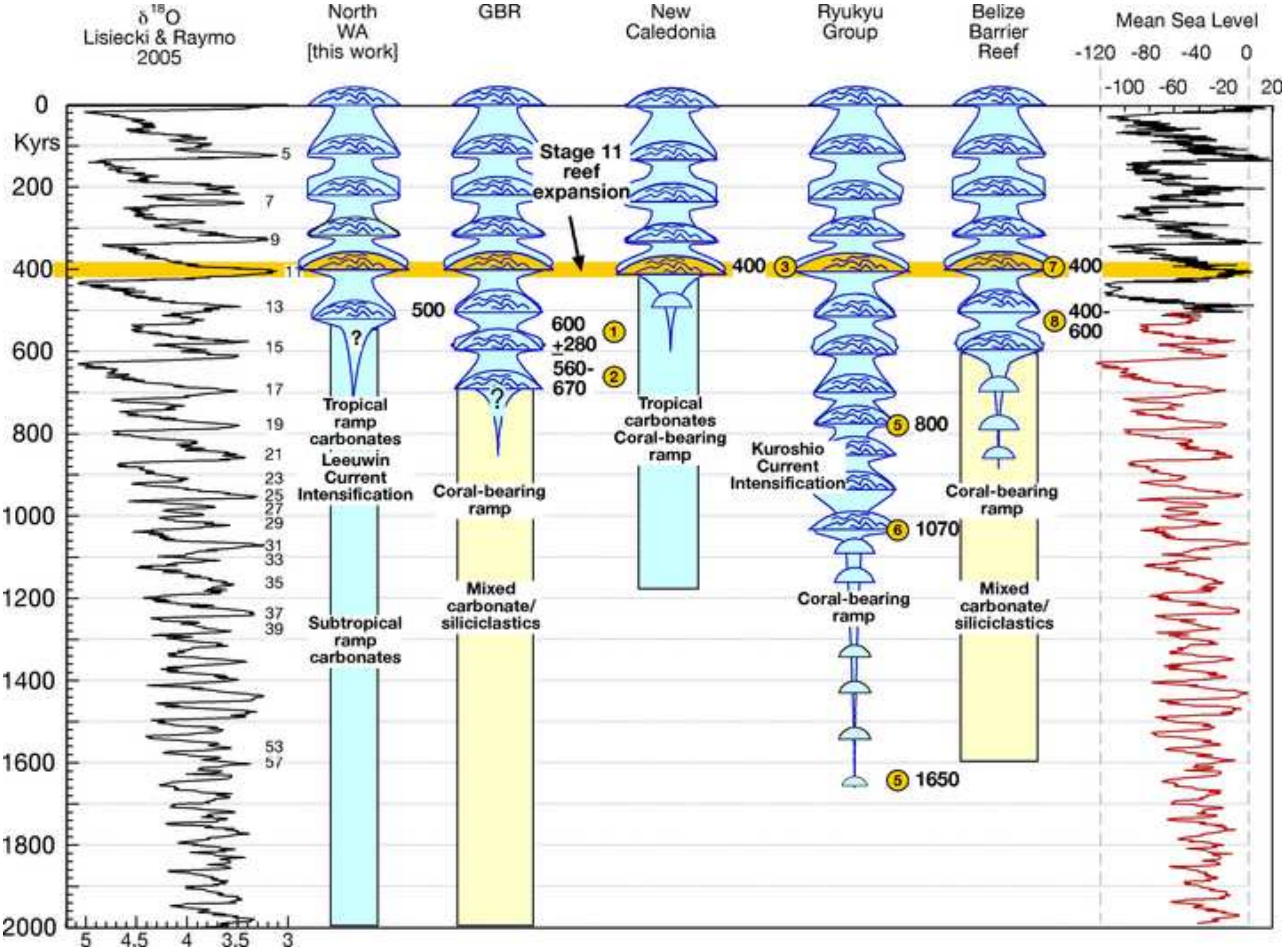

Ooids
Reefs
LR2004
Onset of aridity
0
0.5
1.0
1.5
2.0
TIME (Ma)
5
3.5
Idealized Gamma Profile
Intensity of Australian Monsoon
Leeuwin Current intensity

Figure 9


δ^{18}O
Lisiecki & Raymo
2005
North
WA
[this work]
GBR
New
Caledonia
Ryukyu
Group
Belize
Barrier
Reef
Mean Sea Level
-120 -80 -40 0
-100 -60 -20 20
Kyrs
0
200
400
600
800
1000
1200
1400
1600
1800
2000
5 4.5 4 3.5 3
5
7
9
11
13
15
17
19
21
23
25
27
29
31
33
35
37
39
53
57
Stage 11
reef
expansion
500
?
600
±280
①
560-
670
②
?
400
③
⑦
400
⑧
400-
600
⑤
800
⑥
1070
⑤
1650
Tropical
ramp
carbonates
Leeuwin
Current
Intensification
Subtropical
ramp
carbonates
Coral-bearing
ramp
Mixed
carbonate/
siliciclastics
Tropical
carbonates
Coral-bearing
ramp
Kuroshio
Current
Intensification
Coral-bearing
ramp
Coral-bearing
ramp
Mixed
carbonate/
siliciclastics

Author/s:
Gallagher, SJ; Wallace, MW; Hoiles, PW; Southwood, JM

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