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A fine balance: Accommodation dominated control of contemporaneous cool-carbonate shelf-edge clinoforms and tropical reef-margin trajectories, North Carnarvon Basin, Northwestern Australia

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ABSTRACT

The concurrent development of a cool-carbonate Miocene clinoform system and the tropical reef which developed on its shelf in the North Carnarvon Basin is studied. The study, based on seismic interpretation and geometrical analysis, seeks to investigate how the architecture of the clinoforms develops in relation to the advance of the reef-margin, providing a proxy for discussing contemporaneous shoreline versus shelf-edge development. The progradation of the reef and shelf-edge often display a closely mirrored development, although the reef twice advances an order of two to three times the concurrent advance of the shelf-edge. The forced regression of the second advance, as compared to the normal regression during the first, is observed in proportionally higher input of sediment towards advance of the shelf-edge and toe, along with a gentler slope. The inability of the shelf-edge to keep pace with the reef-margin (and by proxy the shoreline) during lower accommodation/sedimentation is a result of the increased volume of sediment required to match reef-margin advance beyond the shelf-edge. Increased accommodation/sedimentation ratios promote higher trajectories where the volumes on shelf and slope are more balanced and the development more closely matched. The observed matched development of reef and shelf-edge during both limited and increased slope sedimentation, suggest that accommodation is the dominant control on the location and trajectory of both 'shoreline' and shelf-edge, and that excess sediment is deposited along the slope.

Keywords Accommodation, Australia, Carnarvon Basin, clinoform, reef, sedimentation, trajectory,

INTRODUCTION

Models for the development of platform and shelves on continental margins were first developed from outcrop analysis but were greatly improved with the advent of seismic stratigraphy. The scale of seismic data allows for the recognition of such large-scale structures, although many of the basic descriptors for the system (like the term 'clinoform') were first applied in outcrop studies (Rich, 1951). As a first approximation, platform and shelf systems can be classified as being of either siliciclastic or carbonate origin, with both systems having distinct characteristics. Carbonate systems, because of their complex biogeochemical nature, can be further divided into non-tropical and tropical systems. Tropical carbonate systems, with the archetypal developments of reefs, tend to be characterized by an aragonitic/high Mg calcite mineralogy, high sedimentation rates, abundant marine carbonate precipitation (both marine cements and non-skeletal grains like ooids) and dominantly phototrophic organisms (James and Jones, 2015). In contrast, non-tropical carbonates tend not to have reefal systems, are dominated by a calcitic mineralogy, lack abundant marine cements and have an abundance of organisms that are not dependent on light (James, 1997; Nicolaides and Wallace, 1997; James and Lukasik, 2010).

The lack of true reef-builders in non-tropical carbonates means that they tend to have shelves that resemble clastic systems, having low-angle slopes and a gentle deep-water shelf break (James, 1997). In contrast, reefal systems in tropical carbonates tend to have a shallow platform with an abrupt platform margin and steep slopes (Read, 1985). These two distinctive carbonate styles (non-rimmed shelf versus reefal platform) therefore tend to occur in cool/temperate, or tropical settings respectively (although not all tropical systems are reef-rimmed). However, on the Northwest Shelf, both carbonate styles occur in the same region, at the same time, and on the same shelf. In the North Carnarvon Basin (Fig. 1), large-scale carbonate reefs with platforms occur in shallow parts of the system, while in deeper water, well-developed clinoforms delineate the growth of a heterozoan carbonate shelf (James, 1997). This unusual juxtaposition of reefal platforms and non-tropical carbonate shelves appears to be unique to this region and provides an opportunity to simultaneously examine the controls on reef and shelf growth.

Clinoforms, which form the basic building blocks of sedimentary shelf growth, are dominantly controlled by sedimentation and accommodation (Johannessen and Steel, 2005; Helland-Hansen and Hampson, 2009; Kertznus and Kneller, 2009; Jones et al., 2015; Anell and Midtkandal, 2017). Variations in sediment input and changes in relative sea-level generate a series of stacked clinothem bodies which prograde, aggrade or retrograde in response to these changes. The trajectory, the path between successive shelf-edges (Figs 2 and 3), delineates the variations in accommodation and sedimentation (Helland-Hansen and Martinsen, 1996; Henriksen et al., 2009). Retrogradational trajectories occur in response to low sediment supply and increasing accommodation. Aggradational trajectories reflect a balance between accommodation and sedimentation. Progradation and ascending regressive trajectories occur when sediment supply outpaces increasing accommodation and the higher the supply, the lower the trajectory. Negative trajectories reflect periods of decreasing accommodation, often associated with truncation, erosion, incision and sediment bypass of the shelf (Muto and Steel, 2002; Carvajal and Steel, 2009; Henriksen et al., 2009; Dixon et al., 2012; Jones et al., 2015). However, despite the extensive literature on clinoforms, there are many unknowns. This study investigates the stratal architecture of a large progradational carbonate shelf-edge system and its relationship to a contemporaneous tropical reef system. In particular it addresses how the ‘reef trajectory’ is linked to the shelf-edge trajectory of the clinoforms. The study aims to address how variations in reef growth and advance are linked to the concurrent growth and stacking of the shelf-edge clinoforms. Ultimately the aim is to address the controlling factors with respect to accommodation and sedimentation and the possibility of isolating these signals.

GEOLOGICAL BACKGROUND

The Beagle sub-basin forms one of four sub-basins comprising the North Carnarvon Basin (Fig. 1) located on the Northwest Shelf of Australia (Hull and Griffiths, 2002). Following the last phase of rifting in the Jurassic along north-trending fault-blocks the basin has undergone thermal subsidence (Veevers et al., 1991; Blevin et al., 1994; Driscoll and Karner, 1998). The Cretaceous is dominated by transgressive deposits composed of shales, marls and fine-grained carbonates (Romine et al., 1997). Late Cretaceous to Eocene sedimentation was dominantly regressive characterized by clastic-dominated hemipelagic and pelagic, often siliciclastic wedges, with occasional fine-grained calcilutites and calcareous shales (Romine et al., 1997; Hull and Griffiths, 2002). Siliciclastic input shifted to dominantly heterozoan carbonate sedimentation around the Eocene–Oligocene transition (Apthorpe, 1988; Bradshaw et al., 1988; Cathro et al., 2003; Sanchez et al., 2012). Australia's progressive northward drift for the last 60 Myr has resulted in a carbonate system that has evolved from dominantly non-tropical to tropical, with reef development becoming widespread in the mid-Miocene and continuing to the present day (Gallagher et al., 2014). In the Early Miocene a series of island arc collisions and contact with the westward moving Pacific Plate caused buckling of the Australian Plate and dextral transcurrent movement on existing lineaments (Baillie et al., 1994). A dramatic increase in subsidence at around 10 Ma on the Northwest Shelf (Czarnota et al., 2013) appears to correlate to a period of increased tectonism that is recorded at many localities on the Australasian Plate (Dickinson et al., 2002). A large influx of siliciclastic material onto the Northwest Shelf at approximately this time (Bare Formation; Wallace et al., 2003) probably relates to this period of tectonism and renewed onshore uplift.

The Oligo-Miocene clinoform-dominated carbonate section of the Northwest Shelf is known as the Mandu and Trealla formations (Fig. 1) in the Carnarvon Basin (Apthorpe, 1988). On the Northwest Shelf the succession is characterized by spectacularly developed prograding clinoforms (e.g. Apthorpe, 1988; Hull and Griffiths, 2002; Cathro et al., 2003). The older portions of this clinoform succession consist of what have been described as heterozoan cool and temperate water carbonates (Cathro et al., 2003; Wallace et al., 2003). The clinothems are composed mainly of transported carbonate grains and unconsolidated fine-grained carbonate (marl) which is locally cemented by dolomite (Cathro et al., 2003; Wallace et al., 2003; Moss et al., 2004). Widespread reef development begins in the mid-Miocene, and these reefs are visible in two-dimensional and three-dimensional seismic data (Power, 2008; Ryan et al., 2009; Rosleff-Soerensen et al., 2012; Belde et al., 2017). On the Northwest Shelf, north-east of this study area in the Browse Basin, extensive reef rimmed platforms developed in the Oligocene and reduced in area through the Late Cenozoic. The most prominent period of reef-building occurred around 15.1 to 9.8 Ma (Belde et al., 2017). The reef build-ups in the Carnarvon Basin are not as extensive as in the Browse Basin and the Carnarvon Basin was probably towards the southern limit of favourable conditions for reef growth (Rosleff-Soerensen et al., 2012).

The build-ups exhibit the typical seismic characteristics of tropical reefs – height–breadth ratio, high-amplitude, pull-ups and lateral extent (Burgess et al., 2013). In addition, the build-ups are present in favourable palaeolatitudes for tropical reef growth and exhibit typical reef geometries and stacking patterns (Burgess et al., 2013). In contrast, putative cool and temperate-water mounds (Feary and James, 1998; James et al., 2000) display markedly different mounded geometries that lack chaotic reflectors and high velocities. Furthermore, the build-ups of the Carnarvon Basin occur in shallow palaeoenvironments, whereas the cool and temperate-water mounds described by James et al. (2000) occur in deeper water around the shelf break.

Three-dimensional seismic shows well-developed atoll and barrier morphologies and cores containing colonial corals also attest to the presence of reefs (Apthorpe, 1988; Power, 2008; Ryan et al., 2009; Rosleff-Soerensen et al., 2012). Outcrop studies of Miocene exposures at Cape Range confirm the presence of deep shelf marls as well as foraminifera–coralline algal skeletal fragment packstone–wackstone and lagoonal facies with scattered corals, gastropods and clams (Collins et al., 2006). The Pilgramunna Formation, which both conformably overlies and laterally grades into the Trealla Formation, has been interpreted as a quartzose beach/barrier facies (Chaproniere, 1984; Hocking et al., 1987). In the Late Miocene, shelf-edge deltas supplied large amounts of siliciclastic material to the area (Sanchez et al., 2012; Prélat et al., 2015) which became highly dissected with numerous gullies (Cathro et al., 2003). At around 10 Ma, progradational clinoforms give way to a more aggradational or retrogradational sediment package known as the Delambre Formation (Czarnota et al., 2013) corresponding to the earlier described tectonic event and increased subsidence on the Northwest Shelf.

METHODOLOGY

The study had access to a number of seismic lines for orientation, age-constraint, and linking individual clinothems between lines, but detailed study focusses on four closely spaced lines, three parallel one sub-parallel oriented north-west/south-east along-strike to the direction of progradation (Fig. 1). These lines were chosen for the level of detail of the reef visualized in the seismic data (Fig. 2).

Eight 'reef-linked horizons' – seismic reflectors which outline clinothems and can be traced back to their termination against the reef – are mapped out. These horizons were chosen because of their high amplitude and ability to trace back to their termination against the reef. This was necessary for the type of study intended as such reflectors mark isochronous surfaces and thus provide a clear location of the reef and the shelf-edge at a particular time. Additionally, one reflector beneath the succession is traced for comparative purposes. This sub-divides the succession into seven reef-linked clinothems (RC 1 to RC 7) and one basal clinothem (C0). Detailed biostratigraphic dating of clinothems ('chronosomes') on a line to which this study has access to (Fig. 1) indicates that the basal clinoform is approximately 17 Ma and the upper boundary likely correlates with a 12.5 Ma reflector (Hull and Griffiths, 2002). While the top and bottom horizon can be linked across to the study area with a certain degree of confidence, linking discreet clinothems across such large distances has some limitations. Two clinothems, with marked characteristics, can also be given approximate ages (Fig. 1), however, the ages should all be considered tentative.

For each clinothem several geometric parameters are measured or calculated (Fig. 3). The clinothem average vertical thickness (CAVT; Anell & Midtkandal 2017), can be used to 'normalize' values as it provides an average value of amount of sediment within a clinothem. Previously a set distance back from the shelf-edge was used to determine the area in which to calculate the CAVT. In this study the shelf break of the underlying clinothem (or if retrograding the overlying clinothem) is used, which is thought to provide an even more valid comparative value than an arbitrary fixed distance, since it marks a point where depositional processes change (Fig. 3).

For clinothems with a complex depositional architecture, a point using the intersection of the uppermost and lowermost inflection, despite this not being an actual shelf-edge/rollover, is used (Fig. 3). On some lines the reef truncates underlying clinoforms making the original termination of the reflector against the reef difficult to establish and hence also the reef trajectory, reef advance, reef to edge distance and so forth. These values are denoted with an asterisk (Tables 1 and 2) and should be considered very poorly constrained.

The ‘reef-trajectory’ is essentially the overall angle of the front of the reef build-up between the terminations of the clinoforms bounding the clinothems. This trajectory is slightly harder to establish as compared to the shelf-edge trajectory which has mathematically defined points between which to measure. There are some issues in measuring this value, notably that the clinoform terminations are often poorly defined and the front of the reef creates a contorted mix of high impendence reflections. The trajectory was measured using the termination of the clinoforms, although disregarding the pull-up effect of the reef, and the general trend apparent in the reef front. While these values will contain some degree of error, the similar trend in trajectory between the lines suggests that the measurements provide a reasonably good value.

For depth conversion, the use of a velocity of 3900 m/sec is based on the average velocity of the studied succession (ignoring the reef) within the Sable 1 and Brigadier 1 wells (Figs 1 and 2). The interval spans *ca* 1150 to 1250 ms in the Sable 1 well and 1000 to 1400 ms in the Brigadier 1 well. Therefore, the use of this velocity is a simplification, as the studied succession spans down to around 1800 ms, there are velocity variations along strike within a clinothem and differences between clinothems and compaction has not been taken into account. Thus, all vertical measurements and angles might in reality show minor variations from the values provided, but this has little effect as the study is dominantly comparative as opposed to quantitative. All values are corrected for tilt of the shelf. An initial gentle dip of 0.3° is assumed and all values are corrected accordingly. However, because the tilt of the shelf varies along its length there is some uncertainty in the exact values of measured angles.

RESULTS

Minor reef build-ups may have occurred prior to those observed in the studied succession. However, the first clear indications of reef growth on the shelf occur during a period of more aggradational development (average shelf-edge trajectory *ca* 4°), as compared to the strongly progradational clinoforms beneath (*ca* 0.2°; Fig. 2). The development of the reef follows a similar pattern on the four studied lines: an early steady slow advance during RC 1, a large advance (termed advance 1 – Adv. 1) during RC 2, an intermediate to slow period of advance during RC 3 to 5, a second significant advance (termed advance 2 – Adv. 2) during RC 6 and a final period of near standstill during RC 7 (Fig. 2).

The shelf-edge trajectory of RC 1 to RC 5 varies but is always ascending regressive marking a positive accommodation:sedimentation (A:S) value where S is higher than A. The shelf-edge trajectory flattens or falls below zero during RC 6 followed most often by a retrogradation during RC 7 (Fig. 4). Overall the succession at first steepens (slope angle typically peaks during RC 2 while foreset slope peaks during RC 3) and then smooths out. The last clinothem, RC 7, has the lowest foreset and slope angle (Table 1). The 'edge to toe' (ETT) progressively increases, shortening somewhat during Adv. 2, and increases dramatically during deposition of RC 6 and RC 7 (Fig. 5). The distance between the shelf break and the shelf-edge follows a similar trend to the ETT, generally increasing with a minimum around RC 2 or RC 3. The distance between shelf and break peaks along Lines 1 and 2 during Adv. 2, while it continues to increase eastward, where incidentally on Line 4 retrogradation does not occur (Fig. 2). The reef approaches the shelf break during each major advance, progressively getting closer over the course of the deposition of the succession, and the depth between the reef and shelf break, becomes shallower. However, during the period between advances (RC 3 to RC 5) the distance to both the shelf break and the shelf-edge remains fairly constant, and the depth from the reef to the shelf break remains very close to 200 m (Fig. 4).

Clinothem average vertical thickness and normalized values

The clinothem average vertical thickness (CAVT) (Fig. 3) provides a value of the average amount of preserved sediment within a clinothem. By dividing measured parameters such as the shelf-edge advance, toe-advance and edge to toe (ETT) by the CAVT, it is possible to normalize values so that they can be compared between clinothems (Anell and Midtkandal, 2017). This method can isolate clinothems with proportionally higher sediment input toward a certain parameter such as building out the shelf-edge or building out the toe.

The normalized values for shelf-edge advance show that RC 2 and RC 6 consistently have high values (excluding RC 2 on line 4 which is moderate), indicating a high contribution of sediment toward advancing the shelf-edge compared to the other clinothems (Fig. 5). The advance of the reef during RC 2 and RC 6, is significantly greater than the concurrent advance of the shelf-edge. The two significant advances which occur are characterized by different shelf-edge trajectories, the first being low but positive (*ca* 1 to 3°) while the second is low to negative (*ca* -1.5 to 0°). The reef trajectory, within the errors associated with correcting for tilt, is generally very close to zero during these two advances. The trajectory of the reef is constrained by its location on the shelf, essentially meaning it can only be flat to positive, unlike the shelf-edge which can descend. Of note is that when comparing Adv. 1 and Adv. 2 the actual shelf-edge advance is similar in magnitude, but the normalized shelf-edge advance values for Adv. 2 are comparatively much higher (Fig. 5). This indicates that sediment is used to a greater extent to build the shelf forward than during Adv. 2 as compared to Adv. 1. This is also noticeable in the topset : foreset ratio where values are much higher for RC 2 than RC 6, meaning sediment is to a much greater extent partitioned in the topset during Adv. 1 compared to Adv. 2. Additionally, the advance of the toe compared between actual and normalized values shows that during Adv. 1 sediment is not used to a great extent to move the toe forward, while during Adv. 2 it is proportionally higher (Fig. 5).

The normalized ETT value is more complex than other normalized values since a similarly high value can be obtained for a long and thick clinothem as a short and thin one, or even a long and very thin one. Within a system with comparative values, however, a high normalized ETT typically indicates clinothems which are long and/or thin, and low values clinothems which are short and/or thick. The ETT shows that the clinothems are overall increasing in length while the normalized ETT values follows a similar trend but shows a dip during RC 2 and slight peak during RC 3 compared to that of the general trend. The dip indicates that RC 2 is proportionally thicker and RC 3 is comparatively thinner (Fig. 5).

Clinothem description

The first clear indications of reef development occur on the top of the lower bounding clinoform C0 (Fig. 2). C0 has a low angle shelf-edge trajectory increasing eastward, and a very high normalized shelf-edge advance decreasing eastward, indicating more accommodation towards the east (Table 1). RC 1, the first clearly reef-linked clinothem, has a high to moderate shelf-edge trajectory and most often a retrograding toe-trajectory. Unlike C0 the actual and normalized shelf-edge advance for RC 1 increases towards the east and the trajectory-angle decreases suggesting an inverse relationship with higher accommodation in the west. Normalized topset values are consistently the highest recorded for each line, and normalized foreset thickness is generally low, leading to a high topset: foreset ratio indicating that comparatively the most amount of sediment accumulated in the topset during deposition of RC 1 (Fig. 6). The distance between the reef and the shelf break and shelf-edge is the greatest during RC 1 (Fig. 5).

Reef-linked clinothem 2 (RC 2) marks a period of high (high-end moderate on line 4) normalized shelf-edge advance. Shelf-edge trajectories are low to moderate (*ca* 1.5 to 3.0). The reef to shelf-edge advance ratio is between two and three indicating a much greater advance of the reef compared to that of the shelf-edge (Fig. 6). Both reef and shelf-edge advance to a greater extent towards the east (Table 1). The distance between the reef and the shelf break and shelf-edge drops during RC 2 to a value that then remains fairly constant until RC 6, and RC 2 steepens compared to the underlying clinothem (Fig. 4). Along most lines RC 2 has the thickest foresets measured.

Reef-linked clinothems 3 to 5 mark a period of relatively limited reef advance and many measured parameters have intermediate values. RC 3 generally has intermediate values for most parameters although it has the steepest foreset slope (barring line 3) and the foreset is typically quite thin (Table 1). Shelf advance, actual and normalized, generally decreases eastward and the trajectory angle increases (Table 1). RC 4 is quite similar to RC 3 although the shelf-edge trajectory is generally lower and normalized topsets are thinner indicating a decreasing accommodation/sedimentation (A/S) ratio and often a low value for normalized toe advance. The foreset angle shallows compared to RC 3, and the thickness of the foresets is higher. RC 5 marks a period of high normalized toe advance which continues through RC 6 and 7, also apparent in the increasing ETT values. Along lines 2 and 3 Adv. 2 truncates the top of RC 5 leading to some unsure measurements, including that of the ‘reef trajectory’. On lines 1 and 4 the shelf-edge trajectory is low to moderate; however, it is very low to flat on lines 2 and 3 and the deposits form a very asymmetrical thick slope deposit suggesting deposition was different in the middle section prior to Adv. 2.

During Adv. 2 and deposition of RC 6, the distance between the reef and the shelf break/edge decreases markedly. While the shelf-edge trajectory is low to descending, the shelf break trajectory is typically high. Normalized topset values are low while ETT values are high, indicating significant amount of sediment is deposited beyond the shelf-edge. The advance generates asymmetrical bottom-heavy clinothems along all four lines (Anell and Midtkandal, 2017).

During deposition of RC 7 the reef is more or less at a standstill whereas the shelf-edge retreats on all lines barring Line 4, suggesting that towards the east sufficient sedimentation could counteract the increasing accommodation. The distance between the reef and the shelf break is at its lowest. The clinothem is characterized by a very gentle foreset slope and high ETT, high normalized topset combined with a high normalized toe-advance. Shelf-edge advance, actual and normalized, increases eastward while the trajectory angle decreases. The reef to shelf break and shelf-edge distance increases progressively in the same direction.

DISCUSSION

Rates of sedimentation and reef advance

On a geological time-scale accommodation controls reef development (Kemp and Sadler, 2014), although carbonate platforms are sensitive to a number of factors including temperature, light and current and wave energy, meaning they can also provide indications of changes in climatic, tectonic and oceanographic elements (Schlager, 1989; Rosleff-Soerensen et al., 2016). Oceanographic and climatic conditions (such as light, temperature and nutrients) control the amount and type of sediment available to fill the space (Schlager, 1992; Eberli et al., 2004). Tropical reefs require sunlight and high temperatures and thus most form in the photic zone, around 0 to 15 m, and are restricted to the uppermost 50 to 100 m, with biotically controlled production decreasing exponentially with depth (Bosscher and Schlager, 1993; Schlager, 2000). Waves, storms and tidal energy often prevent reefs from filling all available accommodation and sediment can thus be moved in and out of shallow areas. Excess sediment is transported to the slope and in combination with in-place carbonate production results in progradation of the shelf (Sarg, 1988; Eberli and Ginsburg, 1989; James and Christopher, 1991; Wilson and Roberts, 1995; James, 1997; Feary and James, 1998). Carbonate production extends to several hundred metres in cool-water carbonates as they are only marginally dependent on light and are more akin to siliciclastic margins than tropical carbonate settings (Schlager, 2000; Cathro et al., 2003). In the studied system the shape, size and slope of the clinoforms are remarkably similar to siliciclastic clinoforms (Steckler et al., 1999; Houseknecht et al., 2009;Anell et al., 2014; Patruno et al., 2015; Anell and Midtkandal, 2017;). While the combination of *in situ* production and transport and depositional processes can result in a variety of stratal patterns (Handford and Loucks, 1993), the studied clinoforms are likely controlled and develop in a similar way to a siliciclastic margin.

The reef margin is restricted in how far along the shelf it can advance by the depth of water and can thus serve as a proxy for the shoreline. While the actual shoreline can be located several kilometres away, the reef margin still provides a specific location for the position of shallow water depth. This unique case-study allows discussion on the concurrent development of the shelf-edge and shoreline, which has previously only been theorized. This in turn, allows for speculation into how sedimentation and accommodation control the development of clinoforms. There are, however, some important aspects to consider in the discussion. Rates of sedimentation in tropical and cool-water carbonate factories are different. While sedimentation rates can be comparable on shorter time intervals (10^5 years), probably due to reworking and sediment trapping, cool-water carbonate sedimentation rates are often of the order of ¼ of that of tropical over millions of years (Schlager, 2000). The system under study here clearly contains both tropical to cool-water carbonates with overlap and influence between. However, because this study compares the concurrent development of reef *and* shelf-edge between successive clinothems, and not the reef *to* the shelf-edge, the sedimentation rate will certainly affect the deposition of the system, but less so the comparative results. Thus, the quantitative approach here provides some very pertinent discussion points on shelf development.

In the simplest of terms, the location of the front of the reef is controlled by a certain depth. The energy environment on the shelf will prevent further sediment accumulation which would allow the reef to advance further. Further reef advance occurs in one of two ways: (i) accommodation decreases, moving the shallow-water zone further out onto the shelf; or (ii) accommodation increases and advancement of the reef is accompanied by a matched sediment accumulation on the shelf, maintaining the depth, combined with reef growth. A clinoform is thought to fill available accommodation on the shelf before spilling over into the foreset (Milton and Bertram, 1995). However, as a result of the energy environment on the shelf, the clinoform is often unable to fill all the accommodation space in the topset (Pirmez et al., 1998; Driscoll and Karner, 1999). Thus the actual accommodation – the space available, and the 'depositional accommodation' – accommodation in which deposition is possible, is different. This is evidenced in the clinoforms studied here since the shelf break occurs at a significant depth from the reef indicating a long zone between reef and shelf break in which all accommodation cannot be filled, while deposition and accumulation beyond the shelf-edge and progradation of the clinoform still occurs. Similarly, deposition occurs around the reef, as witnessed by the advancing reef and progressively shallowing shelf break. The complexity of the system is therein highlighted since clearly there are factors limiting deposition on the shelf given the advance of the shelf-edge system without filling the topset, meanwhile the reef advances towards the shelf-edge in essence 'overcoming' the energy conditions, attesting to a complex interplay between deposition/non-deposition and productivity in the tropical and cool-carbonate systems respectively.

Concurrent depositional development of the reef and shelf-edge

How the depth between the reef-margin and the shelf break changes between successive clinoforms is observed. It is assumed that the shelf break (the inflection point which is where the roll of the clinoform commences (Fig. 3), represents a point which is more likely to remain at an uniform depth in relation to the reef as compared to the shelf-edge (rollover) which varies considerably with clinoform geometry. Different scenarios in which the depth between the reef and the shelf break increases, is unchanged, or decreases, combined with four varying shelf-edge trajectories (retrograding, aggrading, normal regression and forced regression) are presented. The result is 12 potential scenarios for the combined development of the reef and the shelf-edge (Fig. 7). Table 2 provides an overview of the observations of each clinothem along each of the studied lines. Often the measured characteristics match well with a proposed scenario.

The shelf-edge trajectories of RC 1 to RC 5 are all associated with normal regression during a period in which accommodation is increasing but sediment influx is high enough to cause progradation of the system, i.e. scenarios 3a to 3c. RC 1 (barring on Line 2), most resembles scenario 3b in which the clinothem produced is in essence ‘identical’ to the previous one, and the reef develops at a position almost identical to the one it held on the clinoform below. This is herein termed and referred to as a ‘balanced’ development.

The transition from C0 to RC 1 is associated with notable changes from prominent low-angle trajectory progradation to retrograding toe and very high proportional deposition in the topset area and the associated stable colonization of the reef. A regional flooding event occurred at the beginning of the Mid-Miocene Climatic Optimum (*ca* 16 to 14.5 Ma; Moss et al., 2004) which may have led to a more stable position of the shoreline allowing the reef to establish itself, and potentially increased carbonate production associated with an increased productive area (Schlager et al., 1994). Meanwhile early deep water flooding conditions were not conducive to high carbonate productivity thus typically promoting a more aggradational geometry (Sarg, 1988). The reef needed to grow rapidly to remain in the photic zone (Belde et al., 2017; Kemp and Sadler, 2014). As relative sea-level rise slowed, reef growth more easily matched the accommodation created, aided by better circulation in shallower waters causing carbonate productivity to increase (Sarg, 1988). This transition is apparent from RC 1 to RC 2. Although they share several traits, RC 1 shows a higher shelf-edge trajectory, indicating a proportionally higher creation of accommodation while RC 2 has a lower trajectory accompanied by a significant advance of the reef. Steeper foresets are typically associated with more limited sediment supply (Driscoll and Karner, 1999; O'Grady et al., 2000; Sømme et al., 2009) which is here assumed given the proportionally thinner foresets and high topset:foreset ratios in RC 1. Further north in the Browse Basin, increased accommodation has similarly been found to be associated with decreased progradation and steepening slopes (Tesch et al., 2018). The 3c scenario is suggested for RC 2 along all lines since the reef trajectory is lower and advances further than the shelf-edge leading to the shelf break depth decreasing. In scenario 3c a clinothem not identical to the one below is created, rather than one with a shorter topset (Fig. 7). The reef moves further out onto the shelf, which indicates that the shallow water zone has advanced further out onto the shelf. Given the positive shelf-edge trajectory this occurred during increasing accommodation and can thus be considered a normal regression.

For RC 3, RC 4 and RC 5 the depth to the shelf break is generally unchanged and overall the reef and shelf-edge trajectories, as well as the reef and shelf-edge advance, are often similar indicating a balanced development (scenario 3b). Single lines show scenarios more closely linked to either 3a or 3c, which would indicate more and less sedimentation respectively in these areas, given that the reef-trajectories are similar (Fig. 8). Similar reef trajectories would be associated with similar accommodation and hence variations would be sediment dependent.

The shelf-edge is located in much deeper water than the reef given the extensive distance between them across a dipping shelf. Therefore, sea-level fall can occur without subaerial exposure of large parts of the shelf. Evidence suggests that throughout the Neogene, while shelfal exposure occurred, the shelf-edge remained submerged (Cathro et al., 2003). Formation of gullies and submarine canyons, and karstification provides evidence for a regional fall in sea-level following the Mid-Miocene Climatic Optimum (Moss et al., 2004; Rosleff-Soerensen et al., 2012). A sea-level fall will force the main area of deposition seaward, and the reef, which is very sensitive to even small changes in depth, will be forced basinward too. The effects seen during RC 6, with significant foreset deposition, asymmetrical bottom-heavy clinothems developing and reef advance with some truncation of topsets are likely the result of a sea-level fall. RC 6 is characterized by a depth to shelf break decrease and flat reef and shelf-edge trajectories, as shown in scenario 4c (Fig. 7). The falling sea-level forces the reef to relocate as the shallow water zone is moved further out on the shelf.

The two advances of the reef are of similar magnitude and as their location is constrained to the shelf the measured reef trajectory is similar. While the forced regression during Adv. 2 shows some differences to Adv. 1 with a lower trajectory and in places minor truncation, the differences are much more apparent at the shelf-edge. Of particular note is the proportionally greater sediment input towards shelf-edge and toe advance as indicated by the normalized values, and the lower topset : foreset ratio. The asymmetry of the deposition, which has been shown to occur during relative sea-level fall and to a large extent bypass of the shelf, is further evidence of relative sea-level fall (Olsen, 2017).

On Lines 1to 3, during RC 7, the reef generally aggrades and the shelf-edge trajectory retrogrades, with all parameters in line with scenario 1b in which the reef more or less matches the rising relative sea-level while sedimentation is too limited on the shelf-edge to promote growth and progradation (Table 2). On Line 4, however, both reef and shelf-edge advance, indicating scenario 3b, and sedimentation and reef production high enough to counteract the rising sea-level. The termination of the extensive reef growth into isolated carbonate platforms has been attributed mainly to decreasing sea-surface temperatures after the Mid-Miocene Climatic Optimum, with changes in current-driven sedimentation also contributing to the final demise (Belde et al., 2017). Drowning of a carbonate platform occurs as a result of rapid relative sea-level rise or of a decline in carbonate production rate (Vahrenkamp et al., 2004). Commonly carbonate production exceeds the rates of relative sea-level rise (Schlager, 2000; Rosleff-Soerensen et al., 2012). During development of RC 7, where the reef is largely aggradational while the shelf-edge is generally retrogradational, it is apparent that reef productivity keeps up with the rising relative sea level while the behaviour of the shelf-edge is more akin to a siliciclastic system and unable to keep up. At the end of RC 7 both systems are drowned, although short-lived periods of renewed reef establishment are apparent on the shelf above the studied succession (Fig. 3).

Sedimentation/accommodation

More aggradational geometries; as the studied succession is in comparison to the underlying clinothems, are associated with a higher A/S ratio. However, the early middle to mid-Miocene successions are characterized by increasing sediment accumulation rates (Hull and Griffiths, 2002; Moss et al., 2004), meaning creation of accommodation was occurring at an even higher rate than that of the increased sedimentation. Sedimentation was greater than accommodation throughout the interval except during RC 7 on lines 1 to 3. This is indicated both by the overall ascending regressive trajectories and the overall shortening of the topset as shown by the advancing reef, thus aside from RC 6, scenario 3 (Fig. 7), associated with A/S > 1. It is thought that as a shelf system progrades the topset area of a clinoform will become larger and if relative sea-level rise is constant the system will become aggradational and retrogradational simply as a result of the increased area (Milton and Bertram, 1995). That is, however, assuming that regression of the shoreline doesn't occur, which could keep pace or even outpace progradation and maintain the size of the topset. As shown in this study it appears that the 'shoreline' (reef-margin) can advance to a greater extent than the progradation of the shelf-edge. The whole studied succession can be shown to match scenario 3c (Fig. 7) and the distance and depth between the reef margin and both shelf break and shelf-edge decreases. The approaching reef margin is associated with increased foreset deposition, lower foreset angles and greater advance of the toe within the studied succession. As the depth of the shelf break became increasingly shallow, the distance between the shelf break and the shelf-edge also generally increased. This suggests that the erosional and depositional processes and the energy environment responsible for creating the shape, size and curvature of the shelf-edge, are likely closely linked to depth.

The shelf break is the inflection point on the shelf where a noticeable angular deviation or marked increase in gradient takes place (Vanney and Stanley, 1983). This point occurs at various depth and distance from the reef-margin (Vanney and Stanley, 1983). The shelf break along non-rimmed tropical carbonate margins can occur at depths of 100 to 500 m (Hine and Mullins, 1983), and in the studied succession at 260 to 130 m. Beyond the shelf-break, the depth changes rapidly and energy dissipates (Hine and Mullins, 1983). The shelf-edge is the point of maximum curvature between the topset and foreset of a clinoform (Van Wagoner et al., 1990; Pirmez et al., 1998; Steckler et al., 1999; Anell and Midtkandal, 2017; Helland-Hansen and Hampson, 2009). The shelf-edge is used to measure trajectory and to make inferences about accommodation and sedimentation. As a result of the geometry of the clinoform, it can vary substantially with respect to both distance and depth from the shelf break. It has also been suggested that sediment redistribution and collapse in clinoforms, can change the position of the rollover and hence the trajectory (Anell and Midtkandal, 2017). The shelf-break trajectory in this study is similar to the shelf-edge trajectory (Table 1). However, often the shelf-break trajectory is much higher and more aggradational, even retrograding. The processes responsible for and controls on location of shelf break compared to shelf-edge need to be examined.

This case study allows for observation of both reef margin (shoreline proxy) and shelf-edge. There is an observed tendency for Scenario 3c and 4c (greater shoreline advance) to develop during lower A/S, and for scenario 3b to develop during higher A/S. In the studied succession, significant reef advance is associated with low trajectories and high normalized shelf advance (Case A), whereas more balanced deposition is associated with higher reef and shelf-edge trajectories (Case B; Fig. 8). Conceptually it is easy to assume that Case A1 (Scenario 3c) tends to develop during limited sedimentation since high sedimentation would drive the shelf-edge into deeper water and increase the distance and depth between reef and shelf-edge (Case A3b; Fig. 8). However, there is a need to consider sediment volume in this case. Comparing a low accommodation (Case A) and a high accommodation (Case B) setting and assuming similar sedimentation it can easily be shown that because accommodation increases significantly beyond the shelf break, the shelf-edge is less likely to keep pace with the reef-margin (see volume/area; Fig. 8). With increasing accommodation, the volume of sediment required to fill beyond the slope to advance the shelf-edge compared to the volume of sediment required to fill the shelf to advance the reef-margin, becomes less. That is to say, the ratio between the two areas/volumes becomes less and hence a 'balanced' scenario is more likely to develop with increasing accommodation (Fig. 8). This effect is also potentially reinforced by the higher production in the tropical carbonate factory (Schlager, 2000).

For a shelf prism of sediment to keep growing there must be a continuous amount of sediment without which clinoforms shorten and steepen (Schlager and Ginsburg, 1981; Driscoll and Karner, 1999). In the studied system, the shelf shortens and the slope angle decreases suggesting that reef advance was accompanied by increased deposition on the slope. During RC 1 to RC 3, shelf deposition was favoured and the clinothems generally steeper. During formation of RC 4 to RC 6 more limited normalized topset accumulation, higher ETT and lower slope angles are all consistent with increasing sediment towards the slope. From RC 5 onward the normalized toe-advance also increases exponentially as further evidence of increased sedimentation into the basin. Since a 'balanced' scenario can develop during more limited slope sedimentation, RC 1, as well as during higher slope sedimentation (RC 4 and RC 5), the governing control on the location of the reef with respect to the shelf-edge is accommodation (Case A3a/A3b; Fig. 8).

Other possible controls on reef and shelf-edge growth

While accommodation appears to be the dominant control on the behaviour of reef and shelf-edge growth in the Carnarvon Basin, other factors conceivably do affect these two processes. Reef growth is largely produced by photozoan organisms (organisms strongly dependent on light) whereas shelf-edge growth in the Carnarvon Basin is thought to be largely controlled by heterozoan organisms (those not strongly dependent on light) (Cathro et al., 2003). Therefore, environmental factors that are not directly linked to accommodation such as temperature, terrigenous sediment supply, oceanography and nutrient supply could all differentially affect the photozoan and heterozoan carbonate factories (James, 1997). An overall increase in temperature, for example, may increase photozoan carbonate production in the reefal platform (especially since the Carnarvon Basin reefs are near their southern limit), but may decrease or not affect growth in the deeper heterozoan carbonate factory. A decrease in overall temperature would most certainly favour deeper heterozoan carbonate production of reefal platform growth. An increase in terrigenous sediment supply may also differentially affect the two systems, particularly if the supply of clay-size sediments is increased. Clay-size sediment is likely to bypass the shallow water reefal carbonate factory but may severely impact the deeper heterozoan carbonate factory.

Changes in nutrient supply to the shelf will have an enormous differential effect on the two carbonate systems. Reefal photozoan ecosystems are adapted to low nutrient environments (Hallock, 2001) and high nutrient supply generally hinders reef growth (Hallock and Schlager, 1986). This is because in nutrient rich conditions, fast growing algae and other non-photosymbionts can outcompete the photosymbionts like corals. In contrast, an increase in nutrient supply to the heterozoan carbonate factory will be advantageous and may promote increased carbonate production (James, 1997). Thus, an increase in nutrient supply is likely to cause a slowing of reefal platform growth and an increase in heterozoan carbonate production.

Oceanographic changes like increased upwelling would also have a dramatic effect on the two competing carbonate systems. Increased upwelling is likely to both decrease temperatures and increase nutrient levels, both favouring heterozoan carbonate production. The introduction of a shallow, warm-water current (for example, the modern Leeuwin Current on the Western Australian margin; Gallagher et al., 2009) would obviously favour the reefal photozoan carbonate factory over the deeper heterozoan factory.

CONCLUSIONS

The 'reef trajectory' is the path traced by the front of the reef on the shelf over time and serves as a proxy for the shoreline given that reef growth requires shallow photic zone conditions. Generally, the 'reef trajectory' correlates closely with the concurrent trajectory of the shelf-edge suggesting a closely linked control of both systems. As the area (volume) beyond the shelf-edge increases significantly compared to that of the shelf, and the rate of production in a tropical carbonate system is higher, advance of the shelf-edge is less likely to keep a matched pace with the advance of the reef margin during lower accommodation/sedimentation (A/S) ratios, when more sediment is required to build the shelf forward. Therefore, higher A/S ratios tend to generate a more 'balanced' scenario, with closely linked reef and shelf-edge development, because the area/volume required for the advance is more equal. 'Balanced' development was documented during periods associated with both low and high slope sedimentation, indicating that it is likely that accommodation is the dominant control on the location and trajectory of both reef and shelf-edge.

Two periods of low-angle significant advance of the reef occurred during which the reef advanced two to three times more than the shelf-edge. Mid-Miocene flooding generated accommodation and significant advance occurred as sea-level began to stabilize and normal regression drove the reef seaward. Relative sea-level rose throughout the studied succession except for a fall which resulted in subaerial exposure of the shelf but not the shelf-edge and drove the second advance. The advance forced the reef toward the shelf-edge, with limited topset accommodation and significant sedimentation on the slope and toe of the developing clinoform, creating asymmetrical bottom heavy clinothems and proportionally more sediment was input into advancing the shelf-edge and toe.

The reef documents a successive shortening of the topset and shallowing of the shelf break. The approaching reef-margin promoted increased foreset deposition, lower foreset angles and greater advance of the toe. Sediment input on the slope and basin floor is the dominant control on the foreset slope with limited sedimentation promoting steeper slopes and high sedimentation generating gentler slopes. The reef is better able to keep up with rising sea level than the shelf-edge clinoforms, which behave in a more siliciclastic manner and begin to retrograde earlier.

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FIGURES AND TABLES

Table 1. The various values measured and calculated in the studied clinothem succession. Higher than average values shaded in red, lower than average values shaded in blue. The data was used to produce the graphs in Figs 4 to 6.

Table 2. Summary of several of the studied parameters along the seismic lines, the associated scenarios are summarized in Fig. 7. Mod = moderate values >3 to 8 degrees; Mod High = moderate high values 8 to 15 degrees; High = >15 degrees; F = flat -0.5 to 0.5 degrees; Sim = similar, within 2 degrees or within 400 m; U = unchanged (~ denotes values within 20 m with a small (-) marking a slight decrease and (+) marking a slight increase; D = decrease; I = increase; R = reef; S = shelf. * Denotes uncertain values due to truncation of reflector.

Fig. 1. Map of the study area with the two-dimensional seismic data used, map redrawn based on Hull and Griffiths (2002). The location of Cape Range (Collins et al., 2006), where the succession outcrops are marked on the map of Australia. The location of the four studied lines (lines 1 to 4) is shown, and the two wells which were used for velocity conversions (Sable 1 and Brigadier 1) are marked along with the three wells along a stippled line which provided age-constraints based on biostratigraphy (Hull and Griffiths, 2002). The lithostratigraphy of the area (Kelman et al., 2013) is shown to the right including an eustatic sea-level curve (Haq et al., 1987). The four green stippled lines show ‘chronosomes’ from the work of Hull and Griffiths (2002) which can be correlated with clinothems used in this study (see ages below lithostratigaphic column). The Mid-Miocene Climatic Optimum is shaded in orange. The box

below shows an isopach of the studied succession in two-way-time (see map for outline of the box) with an isopach of the reef in the box to the right. The last box shows the position and advance of the shelf-edge along the four studied lines. The shelf-edge of RC 7 (which generally retrogrades) is not marked.

Fig. 2. Detailed profiles of two of the studied seismic lines. The top showing Line 1 with an enlargement of the reef from Line 1 immediately below in the middle. The lower showing Line 4. The location of the lines is shown on the small map. On Line 1 the ages of the successions are based on the work of Hull and Griffiths (2002). The clinothems are marked with their denotation (C0 and RC 1 to RC 7). The shelf-edge trajectory and 'reef trajectory' are stippled. In the enlargement the trajectory of the reef is shown and the two significant advances of the reef (Adv. 1 and Adv. 2) are marked.

Fig. 3. Schematic of a clinothem illustrating the various geometric parameters studied. The clinothem average vertical thickness (CAVT) is defined and explained. The figure is adapted from Anell and Midtkandal (2017).

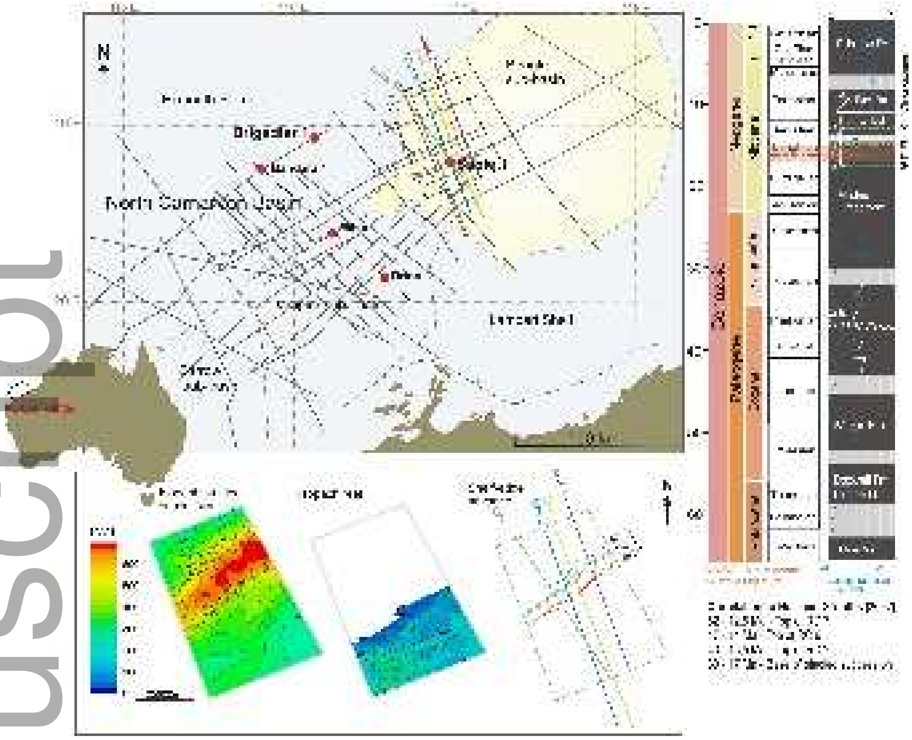
Fig. 4. Graphs showing the relationship and development of several parameters through the studied clinothem succession. The lines are colour-coded and correspond to the colour-code in Fig. 1.

Fig. 5. Graphs showing relationships and development of several of the parameters through the studied succession. Several graphs show a comparison of two parameters along the four lines with one value demarcated with solid lines and the other with stippled lines. The corresponding scale-bar is to the left of the graph for the solid line and to the right of the graph for the stippled line. Some general observations are marked on the graphs. The lines are colour-coded and the colour corresponds to the colour-code in Figs 1 and 4.

Fig. 6. Graphs showing ratios of studied parameters. The upper graph shows the reef advance compared to the shelf-edge advance and the lower shows the ratio between the amount of sediment in the topset compared to the foreset. Lines are colour coded, with the two significant advances of the reef marked with a stippled line.

Fig. 7. The various scenarios that can be produced with respect to the development of both reef and shelf-edge are presented. The three main possible contemporary developments are listed at the top whereby the depth between the reef and the shelf break can increase, remain the same or decrease. For each of these there are four linked scenarios depending on accommodation and sedimentation creating a total of twelve different scenarios. The scenarios are summarized in the table at the bottom left of the page, see Table 2 for the actual observations of the clinothems.

Fig. 8. The figure demonstrates some of the complexity of isolating the sedimentary versus accommodation signal in a clinoform system as illustrated by comparing several cases and the possible associated reef and shelf-edge trajectories. The volume/area box illustrates one of the main findings of the study by showing the differences in volume/area between shelf and slope sedimentation and how this will significantly impact the development of the clinothem. The base case and cases A and B are referred to in the discussion and show how variations in increasing accommodation and sedimentation may impact the reef and shelf trajectory.



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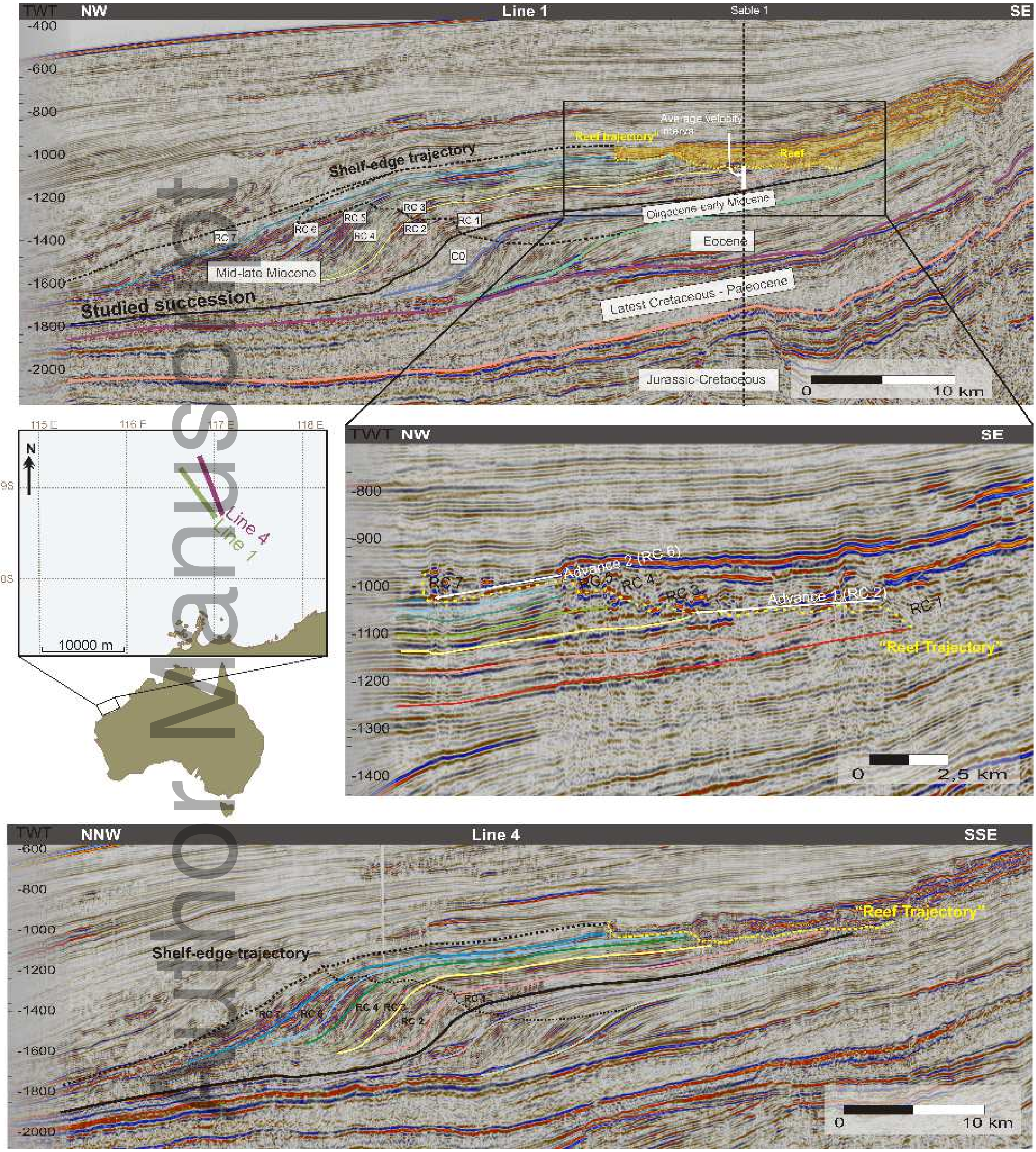

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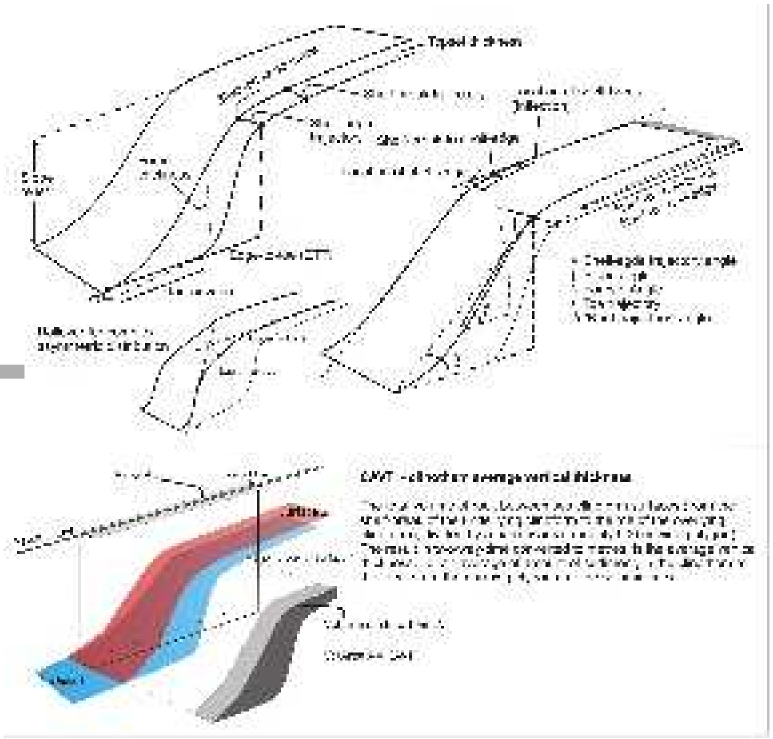

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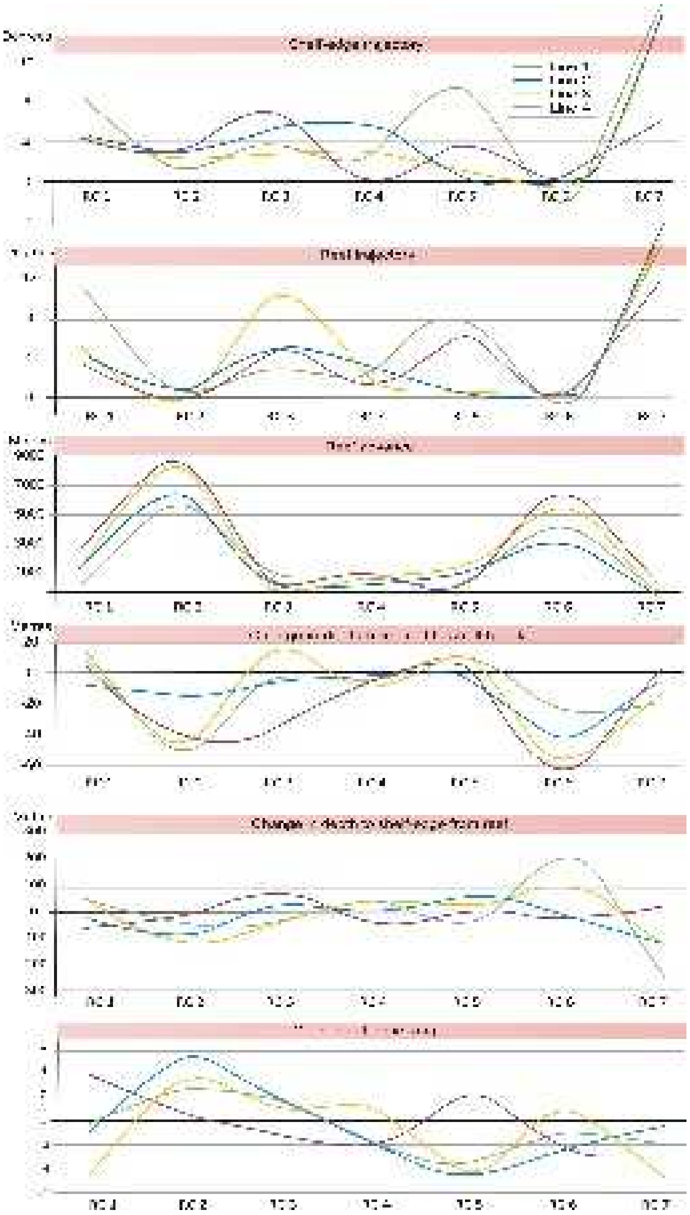

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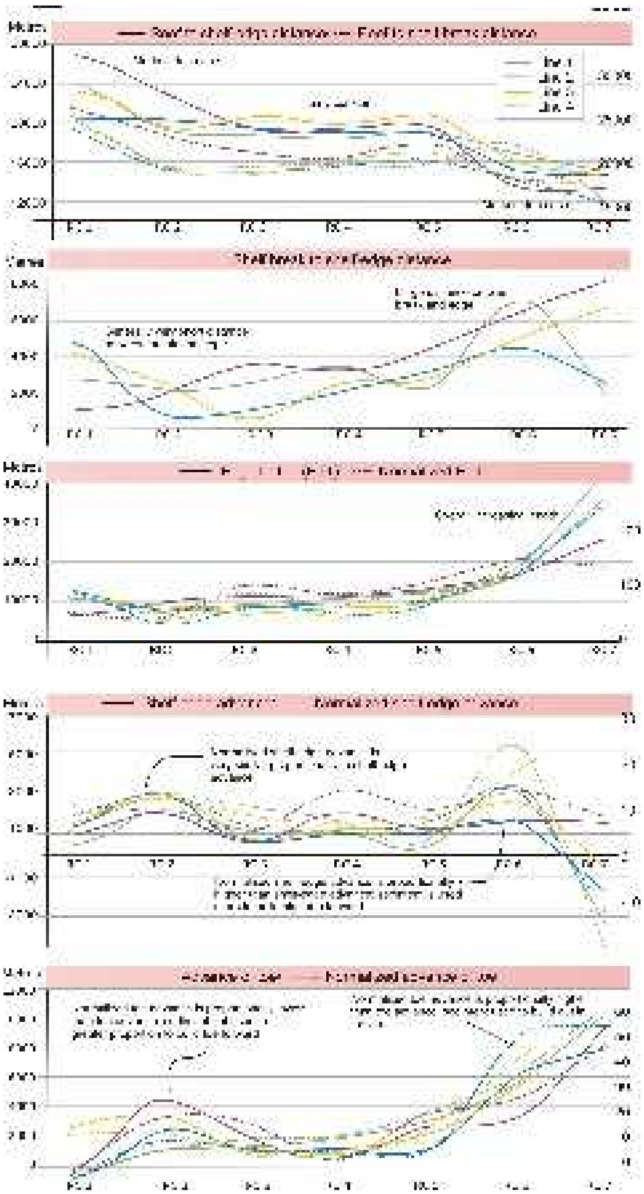

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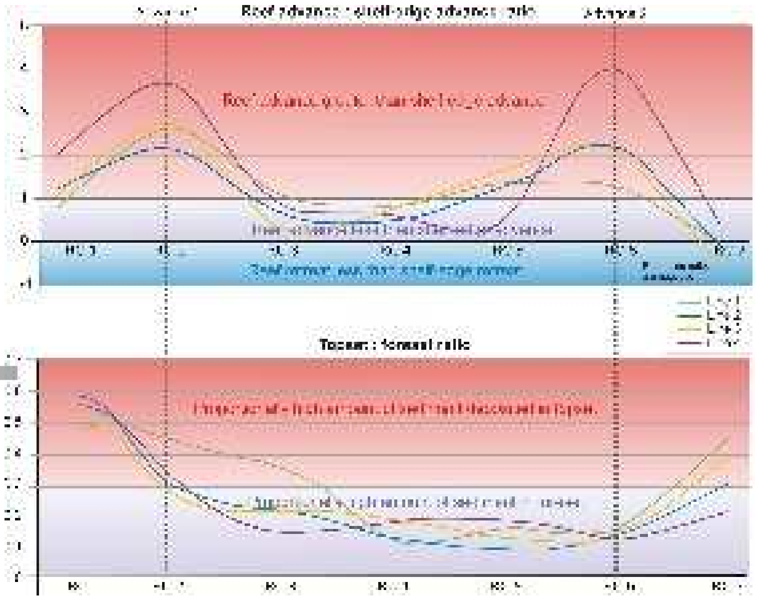

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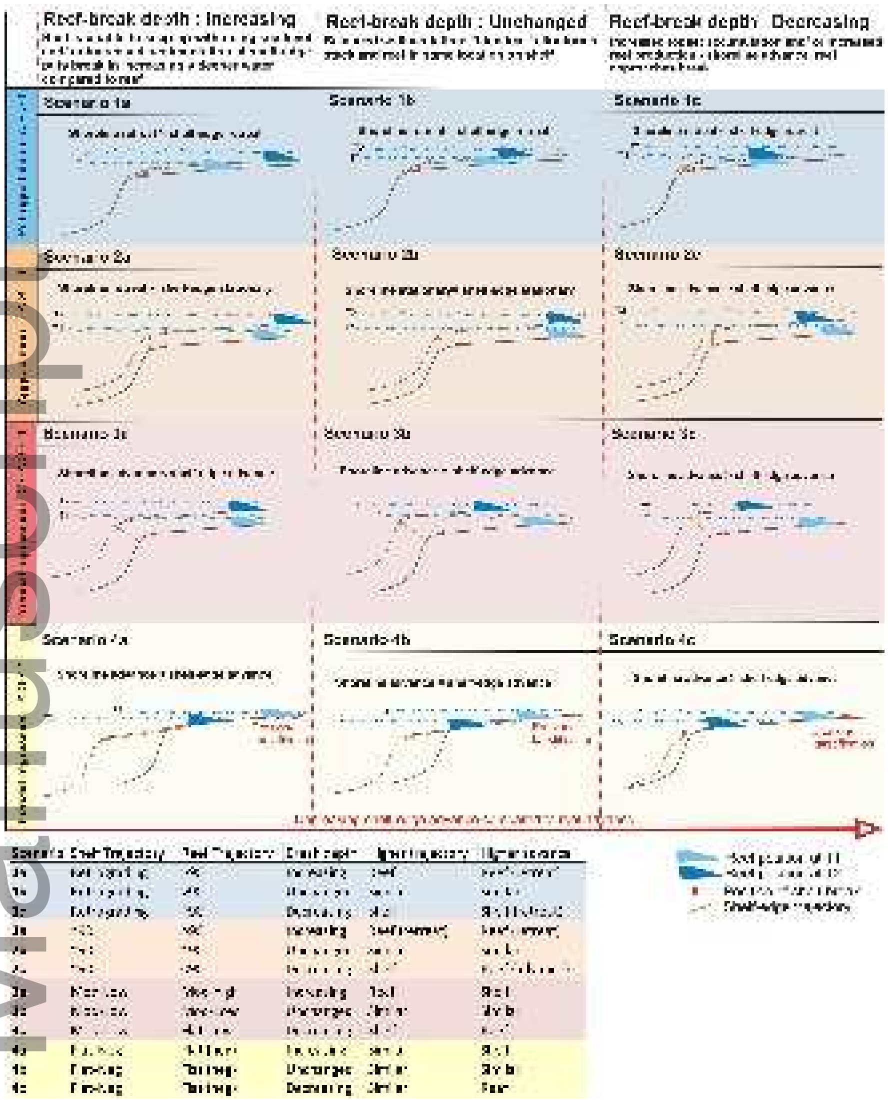

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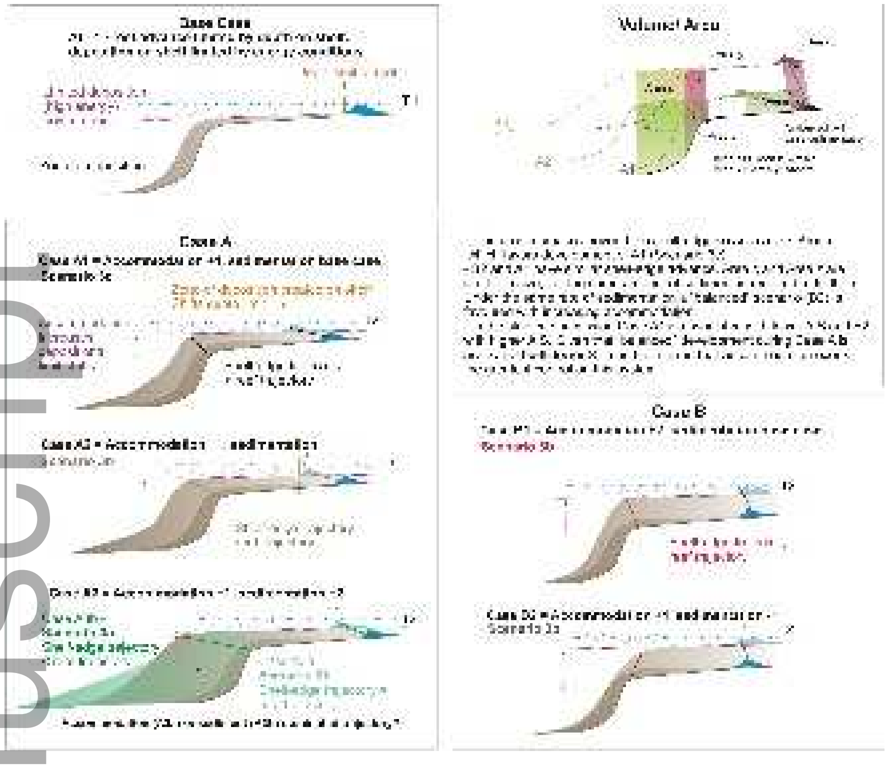

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