Accepted Manuscript

Title: Seismic geomorphology and growth architecture of a Miocene barrier reef, BrowseBasin, NW-Australia

Authors: Beke Rosleff-Soerensen, Lars Reuning, Stefan Back, Peter Kukla

To appear in: *Marine and Petroleum Geology*

Received Date: 22 February 2010

Revised Date: 22 October 2010

Accepted Date: 4 November 2010

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<http://dx.doi.org/10.1016/j.marpetgeo.2010.11.001>

Seismic geomorphology and growth architecture of a Miocene barrier reef, Browse Basin, NW-Australia

Beke Rosleff-Soerensen (corresponding author)

Lars Reuning

Stefan Back

Peter Kukla

Geologisches Institut, RWTH Aachen University, Wuellnerstr. 2, 52062 Aachen, Germany

Tel.: +49-241-95732; fax: +49-241-8092151.

E-mail-adress: soerensen@geol.rwth-aachen.de

Keywords: 3D-seismic ; platform evolution; growth history; relic atolls; Cenozoic; North West Shelf;

Abstract

The Cenozoic succession of Browse Basin is characterized by a carbonate system, that developed from a non-tropical ramp in Eocene-lower Miocene times to a tropical rimmed platform in the middle Miocene. The evolution of the platform was unravelled through the interpretation of the seismic geomorphology and borehole data of the middle Miocene tropical reef system. The first reef structures developed during the early middle-Miocene as narrow linear reef belts with an oblique orientation with respect to shelf strike-direction. Subsequently, they prograded towards the platform margin to form a barrier reef with a minimum length of 40 km. The barrier reef itself comprises three distinct ridges separated by progradational steps. The second and third step are separated by a karstified horizon, which is interpreted to represent the global sea-level fall shortly before the Serravallian/Tortonian boundary. The following third ridge formed in a slightly downstepped position during the sea-level lowstand and initial transgressive phase. Further sea-level rise during the early Tortonian first

drowned the barrier-reef system and subsequently also the patch reefs and relic atolls that had established in a backstepped position in the platform interior. The similar evolution of the Browse Basin reef system and other contemporaneous carbonate systems indicates a strong impact of eustatic sea-level changes. Relatively large subsidence rates in the study area possibly augmented the eustatic sea-level rise in the Tortonian and hence contributed to the drowning of the reef system. However, the initiation and final demise of the reef system was also governed by global and regional climate variations. The first seismically defined reefs developed simultaneous to a maximum in the transport capacity of the Indonesian Throughflow, which brings warm low-salinity waters to the North West Shelf. Reef drowning followed the restriction of this seaway close to the middle to early Miocene boundary. This near closure of the Indonesian seaway possibly led to a regional amplification of the global middle to late Miocene cooling trend and hampered the potential of the reef system to keep up with the rising sea-level.

1. Introduction

The Cenozoic development of many Australian carbonate systems is relatively well documented in outcrops, wells and 2D-seismic data. On the eastern Australian margin the Queensland and Marion Plateaus were extensively studied during ODP Legs 133 and 194 (McKenzie and Davies, 1993; Anselmetti et al., 2006). The cool-water carbonates of the Great Australian Bight on the southern Australian margin were the target of ODP Leg 182 (Feary and James, 2000). In comparison, the Tertiary carbonates of Western Australia are less well studied. Collins et al. (2006) give one of the rare examples for an outcrop study of Miocene carbonates in the area. Cathro and Austin (2001) and Cathro et al. (2003) use information from 2D and 3D seismic data to document the development of the carbonate system in the offshore Carnarvon Basin. Carnarvon Basin remains a non-tropical system with prograding clinoforms during the Cenozoic, which is interrupted by a Late Miocene exposure event. In contrast, little is known about the evolution of tropical carbonates on the North-West Shelf. Sparse evidence from well cuttings indicates the presence of tropical reefs in the northern Carnarvon, the Browse and Bonaparte Basin during the middle Miocene (Apthorpe, 1988). Seismically defined build-ups were also identified on 2D-seismic data from the northern Carnarvon Basin (Fig.1), but their interpretation remained ambiguous (Cathro et al., 2003). Due to the limitations of these 2-dimensional datasets it remained difficult to capture the full spatial extent and variation of these tropical carbonate systems. This study provides the first description of the 3D seismic morphology of an extensive tropical reef system from the North-West Shelf of Australia. The spatial documentation in modern 3D-seismic data provides access to greater morphological detail and geometries of reef bodies and in

turn gives insights into the steering mechanisms of platform evolution (Eberli et al., 2004; Schlager, 2005; Warrlich et al., 2002). Carbonate platforms play a special role within the sedimentary systems as they are able to produce their own sediments. They react dynamically to a variety of ecologic controlling factors (temperature, light, current/wave energy, substrate) and through them indirectly to climatic, tectonic and oceanographic changes (Schlager, 1989; Betzler 1997; Reuning et al., 2006a). These factors control type, amount and distribution of the produced carbonate sediment. Vice versa, it is possible to draw conclusions on environmental impact factors from (1) the sediment type, which is long-established practice by microfacies analysis and (2) the large-scale architecture and geometry of the platform. Yet, only few 3D seismic documentations of tropical carbonate systems exist and all of them were published recently. Among the best documented examples is the Miocene Luconia carbonate platform offshore SW-Borneo, comprising a large area of detached platforms that developed on the crests of tilted fault blocks. Vahrenkamp et al. (2004) and Zampetti et al. (2005) described the architecture of some of the numerous detached carbonate platforms of the Luconia province. In addition Zampetti et al. (2004) focussed on the documentation of landslides at the flanks of one of these platforms. Another prime example documented in 3D is the Eocene to Miocene carbonate buildup of the Malampaya region offshore Palawan (Grötsch and Mercadier, 1999). Fournier et al. (2005) refined the Malampaya model by the integration of high resolution 3D-seismic data and petrographic studies from wells. As the Luconia example, the Malampaya buildup formed on a substratum characterized by tilted fault blocks.

This paper focuses on the 3D seismic analysis of an extensive Cenozoic carbonate platform on the NW-Australian Shelf. The study area provides the opportunity to map the seismic geomorphology of a complete attached shelf with a tropical reef system,

covering the full time span from its establishment to its demise. The studied system developed during the middle Miocene above a non-tropical, distally steepened carbonate ramp and drowned during the late Miocene. In the middle Miocene the Browse Basin was situated relatively close to the transition from tropical to non-tropical carbonate deposition on the North-West Shelf of Australia and hence was prone to be affected by climate change. Variations in the transport capacity of the Indonesian throughflow likely had a major impact on the regional climate, which makes the North-West Shelf a key area to study the effect of oceanic gateways on carbonate platform development. The data presented, superbly image the changing 3D-architecture of a drowning reef system, including the shrinking of the platforms, the backstepping of reef growth and the formation of isolated relic reefs (*sensu* Betzler et al., 1999). For the first time in NW-Australia a seismic-geomorphologic interpretation allows a detailed reconstruction of the morphology and architectural changes during the drowning of an attached carbonate platform.

2. Geological, tectonic and stratigraphic framework of the Browse Basin

The study area is located in the Browse Basin, on the North West Shelf (NWS) of Australia (Fig. 1a). The Australian NWS is a passive continental margin stretching from the SW to the NE between 21°S and 13°S latitude. The Browse Basin lies at the south-eastern margin of the Timor Sea between the Scott Plateau to the west and north and offshore portions of the Precambrian Kimberley Block to the east. It is part

of a series of long-lived sedimentary basins on the NWS. Adjacent basins are the Canning Basin to the south and the Bonaparte Basin to the north (Fig. 1b; Harrowfield and Keep, 2005). Structurally, the central Browse Basin represents a margin-parallel half-graben system, dipping towards the continent (Struckmeyer et al., 1998). Its oceanward border is defined by the Scott Reef Trend, a fault-bound structural rise (Fig. 2). Browse Basin is probably underlain by a west-dipping detachment and displays a pond-like morphology (Fig. 2b); AGSO, 1994).

The NWS developed following a single phase (Kaiko and Tait, 2001) or two phases of rifting (Veevers and Cotterill, 1978) associated with the break-up of Greater India from Western Australia. The final phase of rifting in the Middle Jurassic-Early Cretaceous probably generated the dominant structural trends in the Browse Basin. After tectonic activity had ceased in the Aptian, a thick sequence of passive margin sediment was deposited in the Browse Basin, and buried the former structural relief (Apthorpe 1988). Since the Eocene, the NWS has moved northward from about 40° to 32°S to its present position (McGowran et al., 2004). Renewed tectonic activity commenced in the latest Oligocene or early Miocene with the collision between Australia's northern margin and the Banda Arc (Baillie et al., 1994). In the Browse Basin, the Neogene compression resulted in the reactivation of Jurassic and older fault trends (Harrowfield and Keep, 2005) and inversion tectonics associated with strike-slip displacement concentrated along the Barcoo fault zone (Keep et al., 2000) south of our study area. In the study area, at the outer margin of the central Browse Basin, normal faulting led to the amplification of the previously buried Jurassic basement topography along the structural relief of the Scott Reef Trend (Harrowfield and Keep, 2005). Accelerated subsidence of the outer shelf is indicated by the present position of the drowned Miocene shelf edge in water depth between 500-1000 meters (Willis, 1988). Contemporaneously to the Neogene subsidence a series

of thick, prograding carbonate clinoforms was deposited over large parts of the Browse Basin (Stephenson and Cadman, 1994). Between the Paleocene and the Miocene the sedimentary succession shows a progressive evolution from deep- to shallow-water facies, as well as from siliciclastic to carbonate sedimentation (Apthorpe, 1988; Stephenson and Cadman, 1994).

The stratigraphic record on the analysed 3D seismic data comprises a sedimentary succession from the Jurassic to the Quaternary. The Cenozoic part of the succession can be divided into three evolutionary stages (Fig. 3):

Phase 1- (Fig. 3, non-tropical carbonate ramp) An Eocene to early Miocene interval, in which a strongly progradational succession of partially argillaceous carbonates was deposited, forming an unrimmed carbonate ramp (Apthorpe, 1988; Reuning et al., 2009).

Phase 2- (Fig. 3, tropical rimmed shelf) Close to the early/middle Miocene boundary, the unrimmed heterozoan carbonate ramp developed into a photozoan-dominated tropical rimmed shelf (Apthorpe, 1988; Reuning et al., 2009).

Phase 3- (Fig. 3, hemipelagic sediments) A late Miocene to recent interval, in which outer shelf hemipelagic sedimentation covered the drowned middle Miocene reef succession.

The focus of this paper lies on the interval of tropical reef growth in the middle Miocene (Figs. 3, 4). On the basis of a characterization of the morphologic evolution of the system, the reasons for the shift of the sedimentary environment will be investigated.

3. Data and methodology

Core pieces of the study are the 3D-seismic surveys Brecknock and Brecknock South (Fig. 2a), two adjacent multichannel 3D-reflection-seismic surveys of high quality and resolution, covering together an area of more than 1000 km². The Brecknock South survey comprises 577 N-S-oriented lines covering an area of 287 km². The Brecknock survey covers 845 km² comprising 896 lines. The dataset is zerophase and follows the SEG European polarity, i.e. an increase in acoustic impedance is represented as a trough (blue colour). Horizontal resolution in the target interval is better than 30 m, vertical resolution is close to 14 m.

This study uses biostratigraphic, lithologic, and log information from the well site Brecknock 1 that is located within the area of the 3D-seismic survey. For time/depth conversion of the seismic analysis, check shot data from well Brecknock 1 were used. New laboratory work included in this study was carried out on ditch cuttings and side-wall cores from Brecknock 1. Bulk sample mineralogy was determined using a Siemens D 5000 diffractometer with a cobalt K α tube. All samples were scanned from 0° to 63° with a scanning speed of 0.02 steps/ s, to obtain an overview of the mineralogical composition. Quantitative proportions of selected mineral phases were calculated following the Rietveld method. The standard deviation (1 σ) of this method, calculated from replicates, is < 2 %.

Five samples from sidewall cores were analyzed for ⁸⁷Sr/⁸⁶Sr-ratios on a Finnigan MAT 262 multicollector mass-spectrometer. Two standards, the NBS 987 (75 ng load) and the USGS EN-1 were measured with the samples. The 2 σ standard deviation of the measurements was 7*10⁻⁶. For further interpretation we used the data normalized to and corrected for a nominal value of 0.710247 for the NBS 987

standard (McArthur and Howarth, 2004). However, normalization to USGS EN-1 would not have changed the interpretation, as the deviation of the values from the NBS-normalized values is insignificant. The Sr-isotope values were converted to ages according to the secular seawater $^{87}\text{Sr}/^{86}\text{Sr}$ -curve of McArthur and Howarth (2004) and McArthur et al. (2001, unpublished data compilation).

Oxygen and carbon isotope measurements of cuttings were analysed at IFM-GEOMAR (Kiel, Germany) on a FINNIGAN MAT 252 Mass Spectrometer with Kiel CARBO device. Analytical reproducibility is $\pm 0.07\text{‰}$ for $\delta^{18}\text{O}$ and $\pm 0.04\text{‰}$ for $\delta^{13}\text{C}$. The values are reported relative to Vienna Pee Dee Belemnite (V-PDB) based on calibrations directly to National Bureau of Standards (NBS-19).;

4. Seismic stratigraphy

The studied succession was subdivided by 5 reflectors (BR0, BR1, BR2, BR3, BR4) into 6 intervals (Fig. 4). Below horizon BR0 seismic facies is dominated by continuous parallel or subparallel reflectors. At this depth, no mounded structures are visible and the shelf shows a ramp-type morphology. Above horizon BR0, at a depth of ca. -1600 ms TWT, amplitudes in the platform area increase abruptly, however, reflectors in the proximal part are hummocky and disrupted. In the more distal platform areas, reflectors are continuous. In narrow elongated belts, reflectors begin to form a mounded morphology. The internal reflectors within the mounded structure show a chaotic arrangement but are characterized by very high amplitudes. The belts show an arc shaped geometry in map view, generally oriented in N-S direction (Fig. 5). They have a length of several kilometres, the largest up to 17 km.

Starting at a depth of around -1580 ms TWT, a mounded structure develops parallel to the shelf edge (Fig. 4). The internal reflector signature of this body consists of hummocky to contorted high-amplitude reflectors while at the same time medium-amplitude reflectors proximal to this structure become more continuous. Basinward of the ridge, amplitudes are low and discontinuous, but become more continuous again on the distal part of the slope.

A second ridge is located above BR1, between -1550 and -1450 ms TWT (Figs. 4, 6). The ridge itself has a mounded external morphology and hummocky high amplitude reflectors. Reflector configuration in the platform interior is largely continuous. The second ridge forms a compact belt and exhibits, due to a high aggradational component, a strong positive morphology. Its position is close to the shelf break. This ridge can be tracked over the whole platform within the dataset (Fig. 6). The width of the structure is locally variable, with an average of 800 m.

While in some places the first and the second ridge build two distinctive structures, they merge laterally and form a more extensive and gradually prograding and aggrading system. The average distance between the fronts of ridge 1 and 2 is around 1900 m. Due to the undulating geometries of ridge 2, the distance can vary locally. The internal seismic facies distribution indicates that platform sedimentation is mainly characterized by smooth and straight reflectors. However, small areas of chaotic or higher amplitude reflectors occur locally.

The third and the fourth interval are separated by a continuous reflector (BR2) (Fig. 4) located at approximately -1400 ms TWT with extraordinarily high amplitudes, particularly in the proximal part (Fig. 7a). The horizon BR2 shows two trough-shaped intermissions in the most proximal part, oriented parallel to the strike direction of the shelf (Figs. 6, 7). The distal trough is wider and deeper than the proximal through. The troughs are 300 to 1000 m wide and several kilometres long. Relatively low

amplitude reflectors infill the larger trough, onlapping its high-amplitude basis. The top reflector of the trough filling has a high amplitude again (Fig. 7b).

In the prolongation of the more distal trough a circular feature is visible. It has a diameter of approximately 2200 m and in cross-section also shows a trough-shaped morphology with a filling onlapping onto the trough walls.

The youngest ridge observed in the study area (Figs. 8, 9) occurs in the interval overlying horizon BR2 (Fig. 4). It displays a distinct elevated morphology and, as the other ridges, an internal configuration of contorted high-amplitude reflectors. It forms a very narrow, slightly sinuous belt throughout the whole dataset. Its base is lower than the top of ridge 2, at a depth of -1500 ms TWT, its top is slightly higher at -1400 ms TWT. The interval between BR2 and BR3 is characterized by discontinuous low-amplitude reflectors, while the reflector BR3 itself is very continuous and smooth. The distance between the fronts of ridge 2 and 3 amounts up to ~ 2100 m. The distance between the two ridges may vary, since both systems have an undulating to sinuous geometry. (Fig. 9).

Horizon BR3 is overlain by smooth continuous reflectors of medium amplitude (Fig. 4). Only in the proximal part, this reflector pattern is disturbed by numerous small upward bulges of the reflector with partly higher amplitudes (Fig. 10). Based on this reflector, additional structures with an oval outline could be identified. They are characterized by an elevated morphology consisting of shingling high amplitude reflectors in the rim and lower amplitude reflectors in the center (Figs. 9, 11). They occur preferentially in the most proximal part of the dataset and evolve from areas with a high density of upward bulges in BR3. The interpreted succession is capped by the horizon BR4, which is the first completely smooth and continuous horizon above the described oval structures.

5. Well data

5.1. Data quality

A combination of caliper, gamma-ray, spontaneous potential, resistivity, density and sonic logs were run in the studied interval. Due to the largely poorly-cemented nature of the sediment, especially above a depth of ~ 1690 mbRT, the caliper log indicates a rugose, over-sized hole. The poor borehole-quality affects most log readings. The sonic log indicates erroneously high and density unreliable low readings caused by the hole size and poor pad application, respectively. Only the gamma-ray tool seems to be not seriously affected (Fig. 13). The seismic-to-well tie for the studied interval is based on check-shot data from Brecknock-1. A synthetic seismogram was used to verify the correlation. Since the density readings are unreliable at least to a depth of 2100 mbRT, the synthetic seismogram could only be generated for the interval below the studied section. Generally the ties provide a good correlation in this lower interval.

Several analysis (XRD, $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) were performed on ditch cuttings or side wall cores (Sr-isotope-dating, $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) from well Brecknock 1. Side wall cores were sampled at 1150, 1194, 1275, 1338 and 1379 mbRT. Ditch cuttings were sampled with a 20m-resolution from 1000 to 1280 mbRT and from 1380 to 2000 mbRT. In the interval from 1280 to 1380 mbRT the resolution was increased to 10 m increments. Generally the cuttings are very small (< 500 μm), limiting their use for microfacies analysis. The partly strong recrystallization below a depth of ~ 1650 mbRT further hampers the recognition of bioclasts.

5.2. Stratigraphy

The biostratigraphy is derived from planktonic and benthic foraminiferal data in well reports, which also provide paleoenvironmental constraints. The paleontological information was updated using recent foraminifera biostratigraphy and paleoenvironmental concepts, summarized in Chaproniere et al. (1996) and Hallock et al. (2006) and adjustment to the chronostratigraphy following Gradstein et al. (2004). Foraminifera data for the studied interval were available from Brecknock 1-well within the 3D seismic dataset. Additional age control was provided through a correlation of the seismic markers to the North Scott Reef-well, approx. 50 km to the NNE of Brecknock 1, based on the interpretation of framing 2D-seismic lines. The studied interval between 1000 and 2000 mbRT can be divided in three intervals based on the foraminiferal fauna. The assemblage in the interval between 1000 and 1194 mbRT is a mixture of smaller benthonic rotaliids and long-ranging planktonic species. The benthonic fauna in this interval is common and of moderate diversity, the planktonic fauna is poor in both species diversity and preservation. The presence of *Globorotalia plesiotumida*, *Globorotalia acostaensis* and *Globigerina nephentes* indicate an age range somewhere within the late Miocene to early Pliocene. This interval immediately overlies the uppermost horizon Br4.

The fauna in the interval between 1275 and 1876 mbRT is entirely benthonic, of low diversity and consist mainly of larger rotaliids. Within this interval, the sediments between 1338 and 1619 mbRT are almost devoid of foraminifera. The horizons BR0 to BR3 are part of this interval. A correlation of the horizon BR0 to BR3 to the well North Scott Reef indicates that the benthic foraminifera *Flosculonella bontangensis*

(Middle Miocene, N9) at this site occurs below the lowermost reflector BR0. This indicates an age not older than Middle Miocene for the entire interval.

The benthonic fauna in the interval below 1900 mbRT included larger rotaliids such as *Amphistegina* spp. and *Operculina* spp. but a description of the complete assemblage is not available. The presence of rare fragmented species of *Lepidocyclina* (*Eulepedina*) *badjirraensis* at 1900 mbRT indicates an early Miocene age for this section. At 1919 mbRT a few planktonic foraminifera occur in an otherwise benthonic assemblage. By 1979 mbRT the planktonic content has increased to include a few specimens of *Globorotalia kugleri*, indicating an earliest Miocene age. Other planktonic species include the long ranging species *Globigerina* cf. *venezuelana*, *Globigerina* cf. *woodi* and *Globigerinoides trilobus*.

Calcareous nannofossils were analysed from ditch cuttings of Brecknock 1-Well between 1520 and 1194 mbRT. Most of the 24 analysed samples were barren. A nannofossil fauna could only be identified in five of the samples. The calcareous nannofossil data only partially matches the other stratigraphic data. The fauna in four samples between 1310 and 1280 m represents a mixture of Eocene (*Reticulofenestra bisecta* (CP14b-CP19, Eocene-latest Oligocene), Oligocene (*Coccolithus pelagicus*, *Helicolithus* sp., *Sphenolithus dissimilis* (late Oligoc - early Mioc, CP19a - CN1c) and Miocene to recent (*Reticulofenestra haqii*, CN6 - CN15), nannofossils. We assume that this mixture is a result of reworking. A sample at 1260 mbRT contains a middle Miocene to Recent fauna (*Reticulofenestra haqii*, CN6 - CN15) in accordance with the foraminiferal stratigraphy. Due to these limitations the nannofossil data could not be used to constrain the age model.

For additional age-control $^{87}\text{Sr}/^{86}\text{Sr}$ -ratios of five sidewall cores of Brecknock 1 were analysed in the interval from 1150 to 1379 mbRT (Fig. 13). All except the lowermost sample show a smooth regression. The Sr-age indicated by the lowermost sample is

too young relative to the other samples. This is likely due to diagenetic alteration, since it is the only side-wall core sample used for $^{87}\text{Sr}/^{86}\text{Sr}$ analysis in which the volume of calcite cement exceeded trace amounts. The samples at 1338 and 1275 mbRT show ages of 11.8 (± 0.45) and 11.1 (± 0.2) Ma. The section between these Sr-ages, including the horizon BR3, therefore contains the middle to late Miocene boundary. Horizon BR4 is dated to late Miocene age of 10.3 (± 0.2) Ma by the SWC sample at 1194 mbRT. The uppermost sample at 1150 mbRT also shows a late Miocene age of 9.6 (± 0.2) Ma.

5.3. *Lithology and mineralogy*

The lithologic column is based on analysis of ditch cuttings and side wall cores summarized in the well completion report of Brecknock1 (Fig. 13). Lithologically the studied interval shows little variation, being largely described as partly calcisiltitic calcarenite down to a depth of 1650 mbRT. The content of calcisiltite increases to 35-45% between 1410-1430 mbRT and between 1515 - 1650 mbRT the content of calcilutite reaches up to 30%. One thick, relatively well-cemented and partially recrystallized layer of calcisiltite is present between 1382 and 1410 mbRT.

Estimations based on the analysis of SWCs show that the volume of calcite cement begins to exceed trace amounts in a depth of 1379 mbRT. From 1650 to 2200 mbRT the succession is dominated by strongly recrystallized, slightly cemented (up to 10%), mostly moderately hard limestone with an average 5% vuggy porosity. Calcilutite occurs in variable proportions, but typically makes up between 5 and 25% of the succession. Below 1900 mbRT chert occurs in trace amounts and the clay minerals content increases rapidly. In the bottom part of the section, below 1955 mbRT, the

carbonates are interlayered with 5-15% claystone. This change is also reflected in the gamma-ray signal. Gamma-ray values between 20 to 40 API units are caused by the relatively high clay mineral content. Above this depth the values rapidly decrease towards the BR0 reflector. From BR0 to the top of the section the gamma-ray signal is variable but generally is characterized by API values of less than 20. XRD results indicate that muscovite is the most important siliciclastic mineral above the BR0 horizon, whereas quartz and feldspar are only present in trace amounts. Peaks in muscovite content (up to 5%) correspond to local maxima in the gamma-ray log. Generally the gamma-ray log correlates well to the mineralogical data derived from core material. This indicates that the gamma-ray log is a good high-resolution indicator of the siliciclastic input, although uranium might have a local influence. The carbonate content of the studied interval is high, typically between 95 and 98%. The carbonates consist predominantly of low-Mg calcite (75-92%) while aragonite and high-magnesium calcite are completely missing. The dolomite content on average is ~5 %, but four maxima standing out against this background. The first one being the most extreme with dolomite contents of up to 26% at a depth of ~1740 m. The three following peaks are less pronounced with dolomite contents of about 12% at 1540, 1300 and 1220 mbRT. Four of the described horizons (BR0, BR1, BR3 and BR4) fall each within an interval of elevated dolomite content (Fig. 13). Anhydrite is present between 1740 and 1820 mbRT, the zone of high dolomite values that also includes horizon BR0. Celestite is present in trace amounts above 1180 mbRT.

5.4. $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$

Within the studied interval the $\delta^{18}\text{O}$ values decrease down-core in a stepwise fashion. The first interval above 1380 mbRT is characterized by $\delta^{18}\text{O}$ -values varying in a relatively narrow range around an average of -1,2 ‰. Below this depth, a shift to

lighter values occurs that range between - 1,7 and - 2,7 ‰ around an average of - 2,1 ‰. A rapid shift of nearly 3 ‰ towards minimum values of - 4,6 ‰ takes place at a depth of 1640 mbRT. This second shift is followed by a gradual increase to isotope values around - 2.4 ‰ below 1800 mbRT. The first shift corresponds to the initial increase of calcite cements above trace amounts observed in SWCs. The second shift is correlated to the onset of severe carbonate recrystallization. Whereas the shift at 1380 mbRT is associated with the horizon BR2, no clear connection exists between the other horizons and the $\delta^{18}\text{O}$ signal.

Over the whole section the $\delta^{13}\text{C}$ -values vary between 0,9 and 2.4‰. Three peaks with amplitudes of more than 0.5 ‰ are centred at 1310, 1600 and 1800 mbRT. The isotope values increase down-core from 0.9‰ at 1100 mbRT to 1,6 ‰ at 1180 mbRT close to horizon BR4. This rapid increase is followed by a more gradual increase to 1,9 ‰ at BR3 (~1310 mbRT). After this first maximum the values decrease to around 1.5 ‰ at horizon BR2 (~1380 mbRT). The highest overall $\delta^{13}\text{C}$ -values of 2.4 ‰ are reached at 1600 mbRT about 40 m below BR1. Down-core the isotope values decrease again by about 0.8 ‰ before they increase to the third maximum of 2.2 ‰ at 1800 mbRT, close to BR0. Towards the bottom of the section at 2000 mbRT the isotope values decrease to around 1.7 ‰. All horizons except BR2 seem to be generally associated with relative high $\delta^{13}\text{C}$ -values and occur close to maxima of the $\delta^{13}\text{C}$ signal

6. Interpretation

The interval below BR0 represents the uppermost part of a carbonate ramp (Fig. 4, 14-1). Within this succession, the morphology developed from a gently inclined homoclinal ramp towards a distally steepened ramp, finally approaching a flat-platform morphology. The co-occurrence of planktonic foraminifera with large benthic foraminifera such as *Amphistegina* and *Operculina* in the lowermost part of the section indicates a euphotic open-shelf environment (Hallock and Glenn, 1986). The up-core decrease in planktonic foraminifera abundance and species diversity points to a gradual shallowing of the environment. This relative sea-level fall seems to continue into the lowermost part of the middle Miocene interval as indicated by the onset of reef growth (horizon BR0) at a depth of ~ 1816 mbRT. This shallowing trend can not be explained by the progradation of the carbonate platform, since the site of the Brecknock 1 well was already situated in the inner platform area during the lower part of the early Miocene section. A possible exposure surface at a depth of ~ 1650 mbRT is indicated by the isotope signal (Fig. 13). A parallel rapid depletion of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ -values at this depth could be caused by meteoric influence (Allen and Matthews, 1982). The lighter oxygen isotopes would result from cementation and recrystallization in the presence of $\delta^{18}\text{O}$ depleted meteoric waters, whereas low $\delta^{13}\text{C}$ values would be derived from oxidation of soil-zone CO_2 . The zone below exposure surfaces are typically characterized by negative $\delta^{13}\text{C}$ -values. The lightest carbon values observed in the Brecknock 1 well are 0.7 ‰. This is a strong depletion from the > 2 ‰ directly above the shift, but the values are more positive than normally expected for strong meteoric diagenesis. This might be an effect of the low sampling resolution, ~ 20 m in this part of the section, that likely does not allow to resolve the full extent of the excursion. No karstification structures or strong amplitude variations, which could support the interpretation as meteoric diagenesis, were observed at this depth in the seismic data. However, the absence of such features does not rule out a

possibly short lived exposure event. Subaerial exposure in the Browse Basin during Mid-Miocene sea-level falls is evident from paleo-channels of e.g. the paleo-Fitzroy river beneath the modern shelf (Tapley, 1990). Additionally, early Mid-Miocene karstification was described from the Northern Carnarvon Basin ~ 600 km to the southwest (Cathro and Austin, 2001). The isotope shift occurs above a peak in dolomite content with a maximum of 26 % in a depth of 1740 mbRT. If the depleted oxygen values are interpreted as a meteoric influence, the dolomite peak would be situated directly below the maximum extent of the fresh water lens beneath the exposure surface. Vahrenkamp and Swart (1994) proposed that sea-water circulation beneath fresh-water lenses during early burial could lead to pervasive dolomitization. However, low amounts of anhydrite associated with the high dolomite content rather point to a reflux origin of the dolomitizing fluids. Wallace et al. (2003) propose a reflux mechanism to explain the cooccurrence of dolomite and anhydrite in discrete horizons of Miocene near-shore carbonates from the Carnarvon Basin (North West Shelf). Due to the position of these horizons below siliciclastic-rich units, they suggest a correlation to regressive phases. The increased dolomite content above the horizon BR0 therefore indicates a continuation of the shallowing trend after the initial reef growth.

The precipitation of cements from migrating burial fluids was proposed as an alternative explanation for a parallel depletion in oxygen and carbon isotope values (Sattler et al., 2009). In this case, the $\delta^{18}\text{O}$ signal would be depleted due to the higher temperatures under which the burial cements formed. The carbon isotope values would principally shift to lower values depending on the amount of organic matter being oxidized. The observed up-core decreasing oxygen isotope values towards a depth of 1650 mbRT could be explained by a low permeable flow barrier that would lead to a migration of burial fluids along the barrier. A flow barrier at this depth is not

apparent from the ditch cuttings or SWCs, but the isotope excursion correlates to a change from calcarenites above to recrystallized limestones with vuggy porosity (~ 5 %) below this shift. A temperature of 52°C was measured in a depth of 2100 mbRT in the well. Recrystallization of carbonate under these increased burial temperature hence might explain the oxygen isotope shift, while the relatively low, but still positive, $\delta^{13}\text{C}$ values of 0.7 ‰ might result from an influence of organic matter oxidation in a rock buffered carbonate system (Sattler et al., 2009).

The low sampling resolution and the limitations on petrographic constraints due to the small cutting size prevents an unequivocal interpretation of the observed isotope shift. Due to the lack of a clear indication of sea-level fall in the seismic data we prefer the interpretation as a burial signal.

The ridges that establish on the platform between the horizons BR0 and BR1 are interpreted as reef ridges that occur in first instance in the platform interior (Figs. 5, 14-2). These belts represent the first true tropical reef build-ups.

Once reef growth was established on the platform, the reef successively changed its geometry by basinward progradation and selective growth. The margin-parallel component was strengthened and single reef segments merged to a closed barrier reef at the shelf break (Figs. 5, 14-3). Reef growth in the platform interior did not continue in the same extent and platform interior reef belts were buried by lagoon deposits. In the southern part of the dataset, where comparable reef belts were absent, no barrier reef developed at this stage (Fig. 5).

The initial barrier reef ridge does not yet exhibit such a strong positive morphology as the following stages of the barrier reef (Fig. 4). It is located slightly proximal to the shelf break in the platform interior (Fig. 5). In the following evolution reef growth concentrated on linear reef belts and especially an outer bounding barrier reef ridge. The platform interior is instead covered by lagoonal sediments. The fact that the

closure of the barrier reef controls the environment in the inner shelf area is beautifully proven by the patch reef distribution in horizon BR1 (Fig. 5). The increasing concentration of reef growth on the outer bounding barrier reef represents probably the increasing restriction of the environment behind it. Patch reefs are limited to areas with an imperfect closure of the barrier reef allowing more open marine conditions, whereas behind the barrier reef lagoonal sediments dominate (Fig. 5).

The horizon BR1 corresponds to an interval with elevated dolomite contents of ~ 12 % in the well data. Maxima of similar amplitude can also be observed at BR3 and BR4. In contrast to the dolomite peak above BR0, no evaporitic minerals are associated with these high dolomite values. Additionally, the dolomite peaks at BR3 and BR4 formed during a general rise in sea-level as explained below. A reflux mechanism seems therefore unlikely to explain these dolomite peaks. Background dolomitization, from local Mg-sources such as high-Mg calcite seems possible, but typically creates dolomite contents of only 5-10% (Swart and Melim, 2000). Increased dolomite contents can also occur at non-depositional surfaces (Swart and Melim, 2000), which were exposed to a long phase of dolomitisation by relatively normal seawater. This interpretation fits well into our model for the reef evolution as the interpreted horizons, the borders of the distinct progradational phases are formed by an interruption of the normal sedimentation. These visible breaks in tropical reef growth correspond to times with a strongly reduced sedimentation, the non-depositional surfaces.

Above horizon BR1 another ridge, interpreted as a continuous barrier reef, forms (Fig. 6). It prograded in average 1900 m basinward of the first ridge and has a width of ~800 m. Locally, the two ridge are less distinct and seem to merge due to a more stepwise alternating progradational and aggradational pattern. This reef ridge is

capped by the interpreted horizon BR2. In its proximal part the reflector BR2 has a very high amplitude (Fig. 7a), which, in this case, we interpret to be caused by cementation. We interpret the high amplitudes as an effect of meteoric diagenesis caused by a subaerial exposure of the area. The boundary between the high amplitude and low amplitude areas of BR2 is well-defined and parallel to the general strike direction of the shelf (Fig. 7a). Therefore it can be interpreted as the position of the palaeo- shoreline at that time. In the platform interior reef growth was present on BR2 in form of isolated patch reefs, which were located immediately basinward of the high amplitude area of the horizon (Figs. 6, 7), but not in the area, that we assume to be exposed.

In the proximal part of BR2, additionally, the trough structures described above are prominent. The strike-parallel troughs are visible in amplitude and coherency horizon slices (Figs. 6, 7). Two main sub-parallel troughs are visible, that have an offset of around 4500 m. The troughs strongly resemble structures described by Cathro and Austin (2001) for the Carnarvon Basin. In their example the troughs were interpreted as karstification structures because of their strike parallel orientation and their lack of similarity to any other trough or channel-structures (Fig. 14-4). The circular feature in direct vicinity to the troughs matches the classic dolina, additionally supporting the interpretation of these structures as karstification. Additionally, the onset of reef growth of the third reef ridge above BR2 is slightly lower in position than the top of ridge number 2 (Figs. 4, 14-4). This observation is interpreted as response to a relative sea-level fall, as reef growth reestablished downslope and basinward of the older ridge. The barrier reef survived this phase of regression and does not show any evidence for exposure itself, as e.g. karst structures on the reef top. Still, this event coincides with the possible exposure of the inner platform areas, we discussed above.

An exposure event, as it is recorded in the seismic dataset, should leave a significant signal within the isotopic record. The $\delta^{18}\text{O}$ -values at the depth of BR2 show a slight shift towards lighter values, but the $\delta^{13}\text{C}$ values do not show a clear depletion. The decreased oxygen isotope values could be explained by recrystallization and cementation in the presence of relatively warm burial fluids. This explanation seems likely since BR2 marks the first occurrence of cement contents above trace amounts and the first interval that shows evidence for recrystallization. Hence the isotope signal does indicate an exposure surface at the position of the Brecknock 1 well. Our suggested explanation is that the well site is not located in the exposed area of the dataset (Fig. 7) and does therefore not record meteoric diagenesis. Due to the location in the still flooded part of the shelf, the well contains only a muted signal of the more proximal exposure.

Independent evidence that a sea-level fall is likely recorded at BR2 comes from the Sr-stratigraphy. The age of 11.8 Ma measured ~ 50 m above BR2 fits well to the timing of the global third-order sea-level fall (Ser4/Tor1) that is dated to 11.9 Ma just before the middle/late Miocene boundary (Haq et al., 1987).

The development of the third ridge is characterized by strong progradation in the initial phase, followed by an aggradational phase. The aggradational development of reef ridge 3 indicates a sea-level rise, to which the reef was forced to keep up. This succession leads to a surface morphology with twin ridges, as the older morphology of ridge 2 is not completely covered by the thin, draping lagoonal strata (Fig. 8).

Within the 3D-dataset, the reef can be traced over a distance of 41 km along the shelf break. The third barrier reef ridge is capped by horizon BR3, which represents the termination of barrier reefs in the study area (Fig. 4). An additional indicator for the sea-level rise is the glauconite that first occurs at a depth of 1338 m between the horizons BR2 and BR3 and is documented to a depth of 1275 m after the drowning of

the barrier reef. The glauconite content, which is interpreted to form on omission surfaces during sea-level rise (Erlich et al., 1990), indicates that the drowning occurred during a transgressive interval.

Small upward bulges, which occur in large quantities in the proximal parts of reflector BR3 are interpreted as isolated patch reefs. If analysed from old to young, reef growth in the platform interior began with the development of a horizon of small isolated and amalgamated patch reefs (Figs. 9,10). Subsequently, larger reef patches developed, emanating from areas with a high density of isolated patches reefs on the platform surface, which propagated and coalesced with each other to bigger build-ups (Figs. 9, 10). In a next stage, the isolated build-ups merged to oval-shaped, elongated structures with a raised rim and an empty-bucket morphology (Figs. 11,12). These are particularly present in the proximal area of the dataset above areas of high patch reef density. These structures are interpreted as atolls rising over the platform surface (Fig. 14-5). The largest of the atolls covers an area of around 20 km². Other atolls at the edge of the dataset are probably much smaller, but only partially covered by the data analysed. The interior of the atoll structure is filled by lagoonal or hemipelagic sediments (Figs. 11, 12). The above observations document, that after the drowning of the barrier reef at the platform-margin, reef growth was shifted into the platform interior and led to the development of relict atolls (Figs. 9, 11,12). In total, four atolls could be identified in the horizons overlying the drowning unconformity of the barrier reef (BR3). Reef growth was shifted more and more landwards, which indicates a continuously rising relative sea-level. The minimum age of the final drowning of all reef growth in the study area is given by horizon BR4, which is the first continuous horizon that drapes all atolls. The Sr-stratigraphy gives an age interval from 11.8 to 11.1 Ma for the drowning of the barrier reef (BR3) and an age earlier than 10.3 Ma for the demise of the atolls. The drowning sequence hence

lies entirely within the transgression and highstand following a major third-order sea-level fall (Ser4/Tor1). A sea-level rise is also evident from the foraminiferal fauna. The middle Miocene to earliest late Miocene section between 1876 and 1275 mbRT, is entirely benthonic generally indicate inner-middle neritic (*Elphidium crispum*, *Cycloclypeus* sp., *Operculina complanata*) to very shallow-water conditions (*Lepidocyclina* (*Nephrolepidina*) *howchini*, *Miogypsina* sp.). In contrast, the remaining late Miocene section beginning with horizon BR4 (~1194 mbRT) is characterized by a mixed planktonic/benthonic assemblage that points to a return to euphotic open-shelf conditions (*Amphistegina*, *Operculina*) of inner-middle neritic (*Ammonia supera*) to outer neritic (*Siphonia australis*) depth.

7. Discussion

7.1. Onset of reef growth

The development from a ramp-type to a rimmed platform is a common evolution for carbonate shelves, since the foramol dominated carbonate deposition prepares the shelf for tropical reef growth by stabilization and formation of hardgrounds (Read, 1985). Microfossil analysis of cuttings of well Brecknock 1 seems to indicate that the skeletal association of the early Miocene sediments is dominated by larger benthic foraminifera and bryozoa but lacks aragonitic components such as green algae or corals. A complication is that aragonite is absent from the entire studied section, including the middle Miocene reefal part. It was shown by several studies that aragonite can recrystallize to calcite or dissolve during shallow burial diagenesis

(Melim et al., 2002; Reuning et al., 2005; Reuning et al., 2006b). Brachert and Dullo (2000) demonstrated that aragonite in periplatform settings can be completely dissolved underneath a burial depth of ~ 300 m, which would correspond to a depth of ~ 860 mbRT in Brecknock 1. This selective loss of aragonitic shell material might severely bias the interpretation of fossil assemblages. The trace amounts of celestite (SrSO_4) encountered in the upper part of the studied section can be interpreted as a hint that aragonite originally was present in the sediment (Reuning et al., 2002). Aragonite dissolution can lead to the enrichment of Sr^{2+} in the pore water until celestite precipitates when its saturation state is reached (Swart and Guzikowski, 1988). Celestite was not observed to occur in the early Miocene interval. Additionally the lack of a truly tropical (chlorozoan) assemblage in the early Miocene interval is also demonstrated by the absence of reefal structures in the seismic data. In combination with larger benthic foraminifera, such as *Amphistegina* and *Operculina* this might point to a warm-temperature setting for these deposits (Betzler, 1997). On the other hand, the planktonic foraminifera in this interval are typical tropical species such as *Globorotalia kugleri*, *Globigerina cf. venezuelana*, *Globorotalia peripheroronda* and *Globigerinoides trilobus*. Only *Globigerina cf. woodi* is typically a temperate-water species but ranges also into the tropics; it is e.g. persistently present in the Miocene sections of the ODP Site 806 in the western equatorial Pacific (Chaisson and Leckie, 1993). The planktonic foraminifera assemblage hence suggests tropical temperatures for the Browse Basin already in the early Miocene. A possible explanation to resolve this apparent contradiction could be that the shallow-water in the early Miocene already was tropical but that the sea-floor, where the benthic organisms lived, was exposed to slightly cooler temperatures below the thermocline. Cathro et al. (2003) suggested that the heterozoan dominated Miocene carbonate shelf in the Carnarvon Basin did not built to sea-level but was

characterized by middle to outer neritic water depth of greater than 100 m at the outer shelf. After the following relative sea-level fall the sea-floor likely came within the depth of the tropical mixed-layer. An alternative explanation would be that the chlorozoan associations in the early Miocene were suppressed by increased nutrient contents. The information on the benthic foraminifera assemblage for this interval is too limited to decide whether the environment was meso- or oligotrophic. However, the high clay-mineral content in the lowermost part of the studied section could point to an increased nutrient input from rivers. Siliciclastic input could have played a role in preventing reef growth independent from nutrients. This could be indicated by the fact that the first reefs occurred after the clay content in the sediment decreased to a minimum at the early/middle Miocene boundary. Therefore temperature might not have been the only factor that was important for the initiation of wide spread reef growth. However tropical water temperatures surely were a prerequisite for the development of the reef systems in the Browse Basin. One major reason for the growth of tropical photozoan reef carbonates therefore is probably the northward drift of the Indo- Australian Plate and the resulting dislocation into tropical latitudes. From the Oligocene to the Miocene, the position of the NWS shifted from $\sim 30^{\circ}$ S to $\sim 25^{\circ}$ S (McGowran et al., 2004). This trend continues into the Holocene, bringing the Australian NWS to its present position at $\sim 15^{\circ}$ S. This effect was enhanced by a concurrent global warming phase culminating in the Mid-Miocene climatic optimum (Savin et al., 1985; Feary and James, 1995; Tripathi et al., 2009) that extended the zone of tropical reef growth far to the south. A very similar evolution to the succession in the Browse Basin went on in Eucla Basin in the Great Australian Bight. In the Eucla Basin the Cenozoic was largely dominated by the deposition of a prograding cool-water carbonate ramp. However, this succession contains a tropical interval of Middle Miocene age, characterized by the deposition of a more than 400

km long barrier reef system. Feary and James (1995) account the presence of tropical reef growth in such high latitudes not only to the global warming phase, but also to the influence of a strong flow of the warm-water Leeuwin current. The Leeuwin current is an oceanic current flowing along the Australian west coast in a counterclockwise mode. Thereby, it shifts climatic and facies zones on the Australian West Coast to the South in comparison to e.g. the Australian East Coast. The Leeuwin current is driven by an oceanic pressure gradient between the Pacific and the Indian Ocean, which are connected by the narrow Indonesian passageway, and additionally by coastal winds along the Australian West coast (Gallagher et al., 2009). Biogeographic studies by McGowran et al. (1997) suggested an onset of the current in the Eocene, in response to the accelerated opening of the Southern Ocean. The increasing tectonic closure of the Indonesian seaway lead to a strengthening of the Leeuwin current in the Middle Miocene (McGowran et al., 1997). This period of exceptionally strong flow of the Leeuwin current possibly also acted as a trigger mechanism for the onset of reef growth in the Browse Basin.

On the other hand, the NW-shelf also provides examples of carbonate platforms that contrast this characteristic evolution and thereby contradict the assumption of a common controlling factor. For Carnarvon Basin, immediately south of Browse Basin, there is no shift to tropical photozoan carbonates during the Miocene recorded. Instead, it remains a prograding heterozoan carbonate ramp with various fractions of siliciclastic material (Cathro and Austin, 2001; Moss et al., 2004). Collins et al. (2006) report the occurrence of isolated corals, but their growth potential is not sufficient for true reef structures. Romine et al. (1997) and Cathro et al. (2003) report only smaller isolated seismically-defined build-ups occurring in the sequence. This distribution suggests, that Browse Basin is at the southern limit of conditions favorable for tropical reef growth on the NWS.

7.2. Structural lineaments vs. artefacts

The reason for the position and geometry of the initial reef belts remains uncertain as there is no association with precedent topographies visible. The linear configuration of the belts (Fig. 5) suggests a structural control, however, there is a lack of unequivocal evidence. Reef growth does not, as expected, initiate on the platform edge, but a little bit proximal in the platform interior. Below the first reef belts, there are some lineaments visible in coherency horizon slices as well as in cross sections (Fig. 4). These lineaments are formed by reflector deformation (upward bulging) and locally also small reflector offsets. There are two different options to interpret these structures: either as structural features or as seismic artefacts. The occurrence of seismic artefacts as velocity pullups and diffraction cones below reef bodies due to enhanced seismic velocities in reef-framework carbonates is a classic problem. Bailey et al. (2003) proposed to distinguish faults from artefacts by spatial mapping of the structures and comparison of their distribution to the distribution of reef structures. The fact that these lineaments occur in our dataset exclusively below reef belts and never offset or distort the reef structures themselves supports the interpretation as velocity pull-ups. Additionally, the lineaments gradually disappear with depth. Locally also diffraction cones are clearly visible below the barrier reef structures in our dataset (Fig. 4).

Due to the distortion of the seismics by velocity pullups it is not easily recognized if there are additionally structural lineaments present which possibly control the distribution of reef growth. The existence of structural lineaments would be an

attractive interpretation as it could explain the distribution pattern of early reef growth. However, already Harrowfield and Keep (2005) reported that Neogene faulting is largely confined to the center of the Browse Basin (Fig. 2B), landward of our study area. Additionally, in the vicinity of the Scott Reef Trend (Fig. 2A) outward dipping normal faults with an offset typically not larger than 50 ms TWT and an oblique orientation to the Scott reef trend may occur. The special fault configuration of the area is linked to its tectonic history. The normal faults generated in the late Jurassic rifting phase, are inverted by the Cenozoic transpressional stress regime (Keep et al., 2000) resulting in locally varying tectonic structures (Keep et al., 2000). In many places the net fault offset becomes very small due to the inversion. That means, the steeply dipping structures with very small reflector offset could, according to the regional tectonic regime, well be faults. However, it is difficult to unravel the importance of seismic artefacts, respectively tectonics influence on the features. Still it is important to keep in mind that seafloor topography created by these faults, if present at all, would have been very small.

Therefore, it is not really comparable to settings with reef growth on tilted fault blocks (Wilson, 2000; Wilson et al., 2000; Zampetti et al., 2004), ancient karst morphologies or buried reefs (Lara, 1993). Still, a topography of 10 m would probably have been enough to trigger the preferential settlement of reef growth.

7.3. Exposure

The interpretation of horizon BR2 is based on the combination of several indicators. The high amplitudes of the proximal areas of reflector BR2 (Fig. 7A) are interpreted as cementation by meteoric diagenesis. The troughs and the circular depression

observed in the most proximal area of the dataset are an additional striking attribute of this reflector (Fig. 7). Already the morphology, especially of the circular feature interpreted as a doline, strongly suggests a karst origin of the structures. The fact that all the structures appear on the same level, the horizon BR2, which is additionally characterized by the high amplitudes, indicate a genetic relationship of the features. Examples of karst structures in seismic data for both, circular sinkholes (e.g. Vahrenkamp et al., 2004; Purkis et al., 2010) and elongated karst troughs (e.g. Cathro and Austin, 2001) provide a good reference for the interpretation of these features.

An additional morphologic feature indicating a sea-level drop and thereby indirectly an exposure event, is the geometric configuration of the second and the third barrier reef ridge. The horizon BR2 is interpreted as a non-depositional surface (Fig. 13), representing a break in tropical reef growth. The reestablishment of reef growth after this event is located downslope and basinward of the former reef ridges (Figs. 4, 5). The subtle downstepping pattern is another indicator of a sea-level drop around BR2.

Apart from the morphologic/ geometric configuration, well data should be expected to provide relevant information on the exposure and drowning history. However, the size of the cutting material is too small to offer unequivocal petrographic evidence for an exposure. In cases with a lack of petrographic evidence the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ records are expected to provide insights into the exposure history, as the preserve meteoric signals, even when soils are already removed (Sattler et al., 2009). However, the position of the sampled well in our study area is assumed to be in an area that was not completely emerged by the sea-level drop (Figs. 7, 8). This might be one reason

why we do not receive a distinct signal of the interpreted exposure event in our isotopic record.

Based on the Sr-age dates (Fig. 13) the relative sea-level drop observed in the seismic data can be correlated to the third-order eustatic sea-level fall, right before the Middle to Late Miocene boundary (Ser4/Tor1, Haq et al. 1987).

Results from the Marion Plateau suggest an amplitude of 50+/- 5m for this sea-level fall (John et al., 2004). This is consistent with Apthorpe (1988), who already proposes a subdivision of the Cenozoic sedimentary succession of the North West Shelf into 4 cycles, with the sequence boundary between Cycle 3 and 4 in the Late Middle Miocene. He proposes, that shelf exposure is uncertain, but observes a shift to very shallow facies zones at the end of cycle 3. Similarly, in the Great Australian Bight the late Middle Miocene eustatic sea-level fall is expressed in a hiatus (Feary and James, 1995, 2000). In contrast to the Browse Basin reef, which is draped by hemipelagic sediments, the Eucla Basin system is covered by a Neogene cool-water ramp succession.

7.4. Atoll morphology

The position of atoll growth in Browse Basin is not governed by any seismically resolvable antecedent topography, since the atolls are neither underlain by faults, karst or older buried reefs. However, we can not outrule the existence of subtle topographic features, that are below the limit of seismic resolution. At least for the Browse Basin, the role of topographic control seems to be less important than it is often assumed.

The morphologic development of atolls, if not controlled by basement topography, can provide insights not only to sea-level variations relative to productivity, but also to the paleocurrent regime in the adjacent sea (Betzler et al., 2009).

In our study area, the relic atolls are elongated and oriented perpendicular to the strike direction of the shelf (Fig. 11). The reef rim does not exhibit stronger growth or cementation to one side, at least it is not recognizable in the available resolution of the dataset. Warrlich (2002) clarified the response of reef growth to several influence factors by forward modelling with the “Carbonate 3D”-software. One of the aspects highlighted by Warrlich (2002) is that wind- or current-oriented reef rims should be stronger than wind-protected ones. Additionally, in settings with strong unidirectional currents reef detritus should accumulate preferentially on the leeward side of an atoll and there form a pronounced talus. Strong currents could additionally form drift deposits (Betzler et al., 2009) in the prolongation of the atoll tips. The talus slope around the described atolls in the study area (Fig. 12) does not display a significant asymmetry either. Merely the long sides of the atolls seem to form a slightly steeper inclining slope than the short sides, which points to preferential deposition at the atoll tips. According to Betzler et al. (2009) the steep slopes on the long sides of current-shaped atolls can be caused by sediment winnowing by these currents. However, there are some differences in the geometric configuration of the atolls in their case study of the Maldives and the atolls in the Browse Basin. On the Maldives, the atolls are arranged in a chain and separated by relatively narrow channels, enhancing current strength. The Browse Basin atolls are more isolated and scattered over the platform area (Fig. 11).

Furthermore, there is no additional evidence for a strong influence of currents, as for example, drift deposits, submarine dunes or moats or erosional features with low angle reflector truncations. These factors lead to the hypothesis, that currents might

have played a role in shaping the atolls, but no particularly strong currents were active. Rather the effect could be a result of tidal streams.

Adams and Hasler (2010) provided a theory, in which the aggradational potential of a reef platform is dependant on the ability to produce slope sediment. This ability is in turn, dependant on the ratio between the sediment-producing area and length of reef perimeter. This ratio, in turn, is dependant on absolute size (surface area) and shape of the platform. With a given shape (e.g. a circle) reefs with a larger surface area, have a smaller perimeter/surface-ratio and thus should have more aggradational potential than small ones. For reefs with the same sediment producing surface area, more compact (circular) reefs should have a better aggradational potential than elongated reefs with a higher perimeter/surface ratio. Concerning relic atolls, we do not see evidence for such a theory, as all of them have nearly the same life-span independent of their significantly variable size. As all our atolls are similarly elongated in a ratio of 1:2.5, we can not provide any information on the influence of the shape. However, we believe, that the correlation of size and life span does not apply for reefs with an empty-bucket morphology, because the sediment producing surface is limited to the rim in this case.

7.5. Drowning

The two principal controlling mechanisms of carbonate platform drowning are either a rapid relative sea-level rise and/ or the decline of the carbonate production rate. As the growth rates of tropical reef systems commonly exceed the rates of relative sea-level rise, in most cases a decline of carbonate production due to environmental

deterioration has to coincide with a phase of sea-level rise to submerge a reef system.

In our case study, the last barrier reef generation is preceeded by an exposure event, but the barrier reef displays strong aggradational growth (Fig. 4) pointing to a fast relative sea-level rise during their final evolution stages. The Sr-ages indicate that the drowning of the barrier reef took place between 11.8 and 11.1 Ma during a rapid third-order sea-level rise (Fig. 13; Haq et al., 1987). This eustatic signal was likely enhanced by the subsidence of the outer Browse Basin (Willis, 1988).

Contemporaneous with the drowning of the barrier reef, the carbonate system backstepped and atoll structures were established in more proximal areas (Figs. 9, 12). These atolls drowned between 11.1 and 10.3 Ma during a further sea-level rise. An exposure event preceeding a subsequent sea-level rise is suitable to weaken a carbonate platform (Vahrenkamp et al., 2004). However, an exposure event alone can not account for the demise of a vital reef system as there are many examples of platforms that survived emergence (Kievman, 1998).

Therefore, the crucial factors for the demise of the Browse Basin Barrier reef system have to be searched elsewhere. The decline of the carbonate productivity can be caused by a variety of ecological reasons, as decrease of seawater temperature, enhanced organic productivity or siliciclastic input (Schlager, 1989; Erlich et al., 1990). Oversteepening and self-erosion of platform margins (Schlager, 1981), as well as erosion by currents (Betzler et al., 2009) are additional factors promoting the demise of carbonate platforms. However, there is no seismic evidence for erosion or collapse of the barrier reef or the atolls. The absence of current indicators such as

drift deposits, submarine dunes or moats shows that currents did not play an important role for the drowning of the reef system.

Mineralogic analysis of cuttings as well as the gamma-ray log document only a very small fraction of siliciclastic material in the studied succession (Fig. 13), which is unlikely to reduce water quality to an extent that disturbs tropical reef growth. Particularly because there are many examples of reef growth in mixed carbonate-siliclastic environments with much higher siliciclastic input. For example Tcherepanov et al. (2008) report on a carbonate/siliciclastic mixed system from the Gulf of Papua, which shows a coherent evolution to Browse Basin during the Miocene, beginning with an aggradational phase in the early Miocene, a significant downward shift and exposure event in the second half of the Middle Miocene (Serravallien), followed by reflooding, reestablishment of reef growth and progradation, aggradation and at least partial drowning in the late Miocene.

Elevated nutrient contents are another frequently discussed reason for the demise of tropical carbonate systems (Hallock and Schlager, 1986; Mutti and Hallock, 2003). Mallarino et al. (2002) demonstrated by fluid-inclusion analysis as an independent indicator for waterdepth, that environmental deterioration was responsible for the demise of a Jurassic carbonate platform. Fluid-inclusion techniques indicate shallow water depth for the interval of platform demise. The decline of platform productivity is instead interpreted to be caused by elevated nutrient contents and resulting oxygen deficiency. Blomeier and Reijmer (1999) assume, that elevated nutrient contents contributed in combination with small-scale sea-level changes to the drowning of the Jurassic Jbel Bou Dahar Platform, Morocco. The quality of our cutting material does not offer the possibility to perform $\delta^{13}\text{C}$ analysis on individual components as

foraminifera. Mutti and Hallock (2003) stress how problematic the interpretation of $\delta^{13}\text{C}$ from bulk samples as a proxy for nutrient content of seawater is.

However, the foraminifera assemblage in the middle and late Miocene completely lacks large miliolide foraminifera that would be characteristic for increased nutrient levels (Brasier, 1995). Instead larger benthic Rotaliids (*Amphistegina*, *Operculina*) that are typical for oligotrophic conditions are present before and after the drowning sequence. Additionally, the high aggradational potential of the reef is indicated by the raised reef rim of the barrier reef and the atolls relative to the lagoonal sediments (Figs. 4, 12). This indicates that the growth potential of the reefs was not significantly reduced, but exceeded the aggradation potential of the lagoon at all times. These observations make a strong influence of elevated nutrient contents very unlikely.

In the case of the NWS, the climatic evolution might have played a role. During the Late Oligocene- Middle Miocene the climate was warm, but temperatures dropped in the beginning of the Late Miocene (Collins et al., 2006). The warmest period was the Middle Miocene Climatic Optimum between 16-14 Ma Global cooling began from 14 Ma onward and was probably to a large extent controlled by the decrease of atmospheric pCO_2 (Tripathi et al., 2009).

Additionally, the southward flowing Leeuwin current influenced the water temperatures on the NWS. In first instance, the increasing tectonic closure of the Indonesian seaway in the Middle Miocene lead to a strengthening of the Leeuwin current. However, from ~10 - 5 Ma the oceanic gateway was so narrow, that the Indonesian throughflow and Leeuwin current flow were very restricted (Kennet et al., 1985; Srinivasan and Sinha, 1998; Gallagher et al., 2009). Kuhnt et al. (2004) estimate the time of the narrowest passageway at ~10 Ma. Additionally to this

tectonic restriction the transport capacity of the Indonesian throughflow was strongly reduced by the sea-level fall just before the middle/late Miocene boundary as the passages through the Indonesian archipelago were wide and shallow at that time. The interruption of the Leeuwin current flow and the resulting cooling of the NWS surface waters is contemporaneous to the global cooling phase. Thus there are no warm currents active to compensate for the global cooling in the Late Miocene. The demise of the Browse Basin reef system is possibly an effect of a combination of several unfavorable influences, comprising a general temperature drop in the Late Miocene, a third-order sea-level rise and a temporary interception of the warm Leeuwin current flow.

Similar mechanisms for the establishment and demise of tropical reef growth are documented for the Miocene of the Eucla shelf (Great Australian Bight). Feary and James (1995) assume that on- and offset of the Leeuwin current is the major controlling factor for timing and distribution of reef growth in the Great Australian Bight, which is far more in the south than Browse Basin and generally not very favorable for tropical reef growth.

The rate of relative sea-level rise is the sum of eustatic sea-level changes, subsidence and other tectonic vertical movements. Our reef system is located in a generally subsiding setting on a passive continental margin. Cenozoic differential tectonic uplift due to the transpressional regime occurred throughout the NW-Shelf. However, our study area is located in a tectonically relatively inactive area (Keep et al., 2000), so that the tectonic influence is negligible. However, the relatively strong subsidence in Browse Basin might have contributed to the drowning. The NE-Australian Shelf is a good example to demonstrate the importance of subsidence for the evolution of carbonate platforms. The Queensland Plateau (North-East Shelf),

although in direct vicinity to Marion Plateau shows a contrasting evolution. While Marion Plateau was emergent in the Late Middle Miocene, the Queensland Plateau remained submerged due to co-occurring subsidence pulses, especially the one starting at 13.7 Mio. a (Fig. 14; McKenzie et al., 1993). The clear sequence boundary from Marion Plateau is there replaced by a facies shift from tropical to nontropical, triggered by the general climatic cooling and the submergence by subsidence pulses. DiCaprio et al. (2010) recently provided a study with a new approach to explain the strong subsidence on the Australian NE Shelf. They show that mantle processes, namely the overriding of subducted crust slabs, can locally induce accelerated subsidence. However, this concept is not equally applicable to the NWS, because the subducted slabs were results of the southward dipping Eocene Melanesian subduction zone, that was limited to NE-Australia.

From our dataset alone it is not possible to conclude if the drowning of the tropical reefs was completed during the earliest late Miocene or if reef growth continued in other parts of the Browse Basin. At least, the structure of Scott Reef, which is located north of our study area, survives several re- and transgressive phases and continues to grow until the present. Data from a well penetrating this structure does not indicate conclusively if the growth record at this site was continuous or interrupted by an exposure (Apthorpe, 1988).

8. Conclusions

By a combination of 3D-seismic interpretation and well data it was possible to unravel the evolution of the Miocene carbonate system in Browse Basin for the first time. The

turnover from a non-tropical distally steepened ramp to an extensive tropical reef system in the Browse Basin took place during the early Middle Miocene. The first reefs developed as narrow linear reef belts with an oblique orientation in respect to shelf strike-direction. Antecedent topography, which is often assumed to govern the position of reef initiation, could not be observed to control reef distribution in the Browse Basin. During the Middle Miocene the reefs developed to a barrier reef system, that was partially exposed at the Serravallian/Tortonian boundary, reflooded, backstepped and –at least in the studied area- finally drowned during the Late Miocene.

For the onset of tropical reef growth we assume a predominantly climatic control, while the following evolution was determined by an interplay of regional subsidence, eustatic sea-level changes and climatic and oceanographic factors. The influence of warm oceanic currents, e.g. the Leeuwin current seems to be an important controlling factor for the timing and distribution of reef growth. The interruption of the Leeuwin current flow in combination with global climatic cooling and third order sea-level variation are assumed to be the major contributing factors to the demise of the tropical reef system. Eventually, the Browse Basin carbonate platform is a beautiful example for the application of 3D-seismic geomorphology and seismic attributes to the characterisation of sedimentary environments and processes.

Acknowledgements

We would like to thank Andre Bornemann from the University of Leipzig for nanofossil analysis. Uwe Wollenberg (RWTH Aachen) is thanked for supporting us with XRD analysis. Many thanks to Cornelia Lutter (RWTH Aachen) for qualified assistance

with tricky literature problems. We are grateful to John McArthur for provision of his LOWESS table for Sr-age calibration.

We would like to thank Geoscience Australia and especially Mrs. Cronin for access to the seismic data. We greatly acknowledge the work of John Reijmer (VU University Amsterdam) and a second anonymous reviewer, who gave detailed and constructive comments on our manuscript. Last, but not least we thank the German Research Foundation (DFG) for funding this project by the research grants Re-2697/1-1 and Re-2697/3-1.

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Figure captions

Fig. 1:

- a) Greater tectonic setting of Australia (redrawn after Harrowfield and Keep, 2005)
- b) Bathymetry of the Australian NW-shelf and subdivision into sedimentary basin units. (Map basis: Geoscience Australia)

Fig. 2:

- a) Bathymetric map of the study area indicating subdivision and structural elements. The study area (Brecknock and Brecknock South 3D-seismic surveys) are indicated in red
- b) Published cross- sections across the (a) Browse Basin (AGSO, 1994, from Harrowfield and Keep, 2005)

Fig. 3:

- a) Topographic overview in time (TWT/ms) of the 3D-dataset on basis of horizon BR3. Location of cross-section in Fig. 4b) is indicated as black line
- b) Seismic composite section through Brecknock and Brecknock South 3D-seismic surveys displaying subdivision into major Cenozoic sedimentary units. For location compare Fig.4a)

Fig. 4:

Seismic section displaying the four evolutionary stages of the reef system separated by the horizons BR0, BR1, BR2, BR3 and BR4. For horizon slices compare Figs. 6 - 10. The three barrier reef ridges are marked by yellow numbers.

Fig. 5:

- a) Semblance horizon slice of BR1, elongated black structures represent the first generation of reef ridges, including the first barrier reef ridge parallel to the margin.
- b) Semblance horizon slice of BR1 with the main facies attributes highlighted. In the southwestern part of the map a barrier reef is resembled by an artefact of an overlying reef ridge, which is not yet present at this stage.

Fig. 6:

- a) Semblance horizon slice of BR2 showing the distribution of facies elements perpendicular to the strike direction of the shelf in SE-NW direction.
- b) Semblance horizon slice of BR2, main facies elements highlighted

Fig. 7:

- a) Amplitude horizon slice of BR2. Red and yellow colours represent high amplitudes, that were probably caused by cementation of the reflector during subaerial exposure of the proximal part. Closeup shows karstification features and location of Fig. 8b. Boxes: Karst troughs; Circle: doline.
- b) Seismic section with karst structures in horizon BR2, for location compare Fig. 8a)

Fig. 8:

3D-morphology of the shelf after the third progradational step of the barrier reef (Horizon BR3). Location of Brecknock 1-Well indicated. The depression to the left is an artefact caused by a recent channel structure.

Fig.9:

- a) Semblance horizon slice of BR3
- b) Semblance horizon slice of BR3, main facies elements highlighted

Fig. 10:

- a) Overview map of the datasets with position of Fig. 11b) indicated
- b) Semblance horizon slice detail of BR3 with pinnacle reefs (black dots)
- c) Seismic cross section displaying pinnacle reefs on BR3

Fig.11:

Horizon slice displaying the average magnitude of the amplitude, clearly distinguishing between framework carbonates and surrounding platform detritus. The cemented and rigid atoll frames are highlighted. Indication of position of the cross-section in Fig. 12b)

Fig.12:

Length- and cross-wise seismic sections of the atolls showing their elevated empty-bucket morphology. Blue: BR2; Yellow: BR3; Pink: BR4

Fig.13:

Table of well data from Brecknock 1 in relation to the interpreted seismic horizons, absolute and stratigraphic age. Origin of the data is stated as follows: DC= Ditch Cuttings; Log= Geophysical Well Log; SWC= Side Wall Core

Fig. 14:

Summarizing sketch of the carbonate platform evolution

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14