Progressive Western Australian collision with Asia: implications for regional orography, oceanography, climate and marine biota

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Abstract

The western margin of Australia has migrated over 30° northward in the last fifty million years. As it progressed, it carried evidence of greenhouse to icehouse climate and ocean transitions in the sedimentary sequences. In the last ten million years Australia collided with the Asian plate to the north, leading to the uplift of the Indonesian archipelago and Papua New Guinea highlands and restricting the interchange between the Indian and Pacific oceans. This created the near "modern" oceanography of the region with the onset of the Indonesian Throughflow and related Leeuwin Current. It also resulted in the ongoing crustal stress along the North West Shelf causing substantial seismicity and faulting. Recent sediment coring by the International Ocean Discovery Program (IODP) and RV *Sonne* has yielded superb palaeoclimatic and palaeoceanographic archives that will uncover details of the evolution of this margin through the late Neogene to Recent. Knowledge of the past evolution of Australia's western margin is essential if we are to better predict the consequences of ocean/climate variability for future climate change.

KEYWORDS: neotectonics, palaeoclimate, continental shelf, sediment sampling

Manuscript received 6 June 2018; accepted 1 December 2018

INTRODUCTION

The northern margin of Western Australia preserves late Palaeozoic rift margin geometries formed from the breakup of Gondwana (Etheridge & O'Brien, 1994; Exon & Colwell, 1994; Longley *et al.*, 2002; Fig. 1). Ribbon-like microcontinents separated from this part of the margin in several rifting events, with the latest rifting phase in the Late Jurassic (Heine & Müller, 2005; Exon & Colwell, 1994; Metcalfe, 1988). The earliest rifting during the late Permian (initial breakup of eastern Gondwana; Sengor, 1987), preceded rift episodes in the Late Triassic–Early Jurassic and Late Jurassic (von Rad *et al.*, 1992; Driscoll & Karner, 1998). Final rifting (latest Jurassic) resulted in the earliest Cretaceous separation of greater India from Australia (Boote & Kirk, 1989; von Rad *et al.*, 1992; Heine & Müller, 2005), manifested today as a series of sedimentary basins (Bonaparte, Browse, Roebuck and Carnarvon, together referred to as the North West Shelf of Australia) along the continent's northwestern margin (Fig. 1). The most recent significant tectonic event was the late Miocene collision between the Scott and Timor Plateaus offshore of north Australia (Keep & Haig, 2010; Haig, 2012), and the Banda Arc (Audley-Charles *et al.*, 1988; Lee & Lawver, 1995; Richardson & Blundell, 1996; Keep *et al.*, 2007; Keep & Haig, 2010; Haig, 2012). This event caused widespread deformation on Timor Island and associated deformation along Australia's northern margin, including localized fault reactivation and inversion (Malcolm *et al.*, 1991; Struckmeyer *et al.*, 1998; Cathro *et al.*, 2003; Keep *et al.*, 1998; Keep & Harrowfield, 2008; Harrowfield & Keep, 2005; Keep *et al.*, 2007). Whilst the northernmost part of the margin was colliding in the vicinity of the present-day Bonaparte Basin (Fig. 1), the margin to the west (most of the Browse Basin, and the Roebuck and Carnarvon basins) had not yet reached the subduction zone, and remains a passive margin.

The collision of a segment of the northern Australian margin with the Banda Arc partially closed the South East Asian Gateway (the only low-latitude connection between the Pacific and Indian Oceans; Hall *et al.*, 2011), as a result of the collision-related emergence of Timor Island. This partial closure strongly influenced regional biogeography and local and regional climate. At present the Australian Plate, with its newly acquired collision material along the northern margin of Timor (Genrich *et al.*, 1996), continues its northward journey at approximately 77 mm/year, with incipient southward subduction of the Banda Sea under the Australian Plate beginning on the Wetar thrust (e.g. Keep & Haig, 2010). The western (non-collided) part of the margin continues to move northwards towards the Sunda Trench subduction zone (Fig. 1) with collision predicted in about 10 million years from now (Nugroho *et al.*, 2009).

The stages of continental collision that produced Timor's orogenic landmass include collision and shortening during the Late Miocene (involving loading and diapirism), a tectonic quiet interval (latest Miocene – Early Pliocene (perhaps related to locking of the subduction system), and a Late Pliocene – Pleistocene phase of uplift, and unroofing as a result of isostatic rebound (Keep & Haig, 2010; Haig, 2012). Bathymetric contours (Haig, 2012) provide a means for visualising

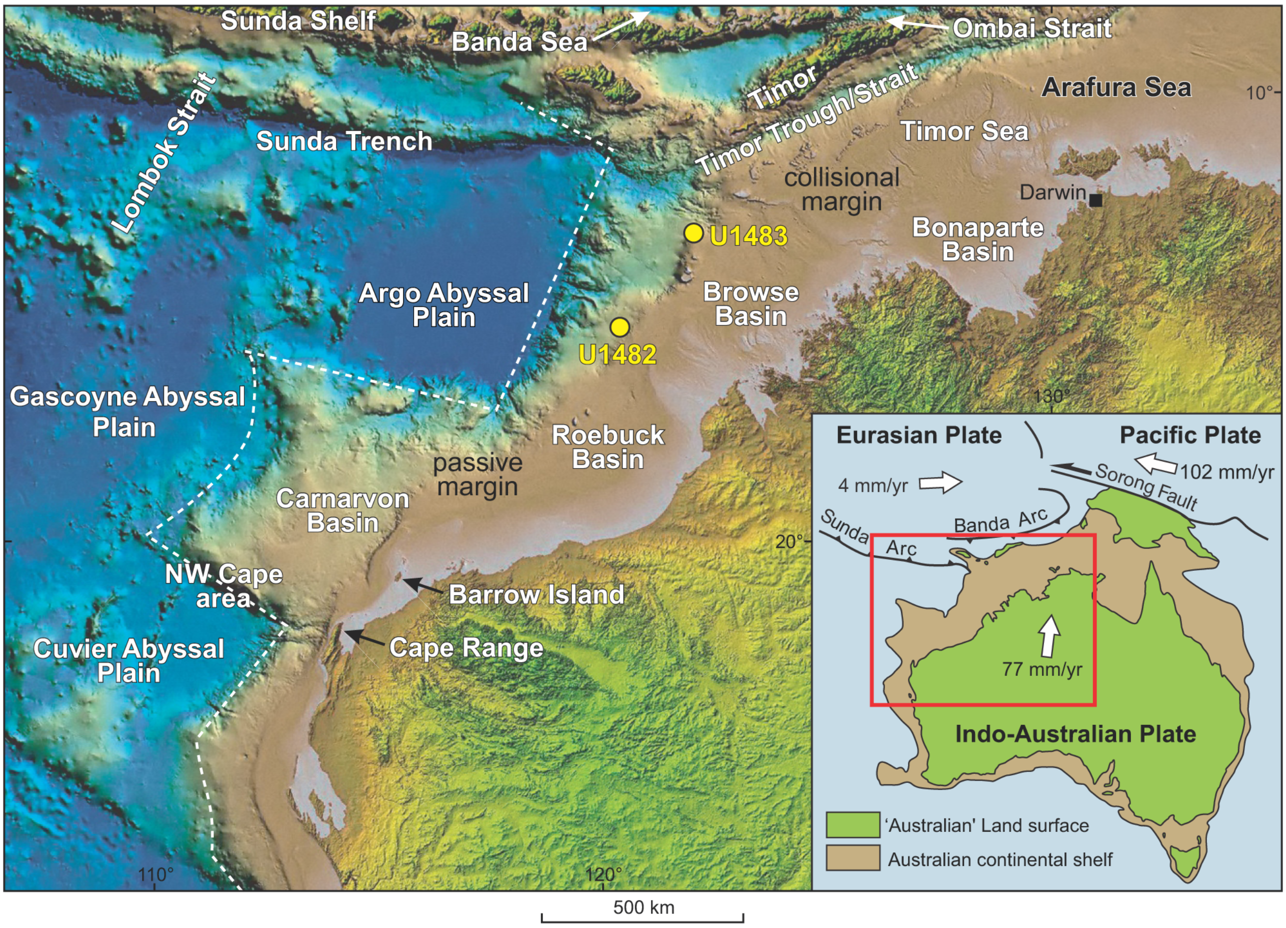

Figure 1. Location map of the northern Australian margin, showing the major offshore sedimentary basins, abyssal plains, and major tectonic elements including the Sunda Trench subduction zone and the collisional pile of Timor Island. Inset shows the major tectonic elements associated with the northwards motion of the Australian Plate. The white dashed line is the continent-ocean boundary. Sites of U1482 and U1483 on the Scott Plateau also shown. The three main exits of the Indonesian Throughflow into the Eastern Indian Ocean are the Lombok Strait (sill depth = 350 m), Ombai Strait (sill depth = 3250 m), and Timor Strait (sill depth = 1890 m).

the topography of the orogenic pile from 5.7 to 3.3 Ma, and indicate a bathymetric gradient across Timor from a northern area (now the exposed Aileu metamorphic complex) to deeper water in the south, east and west. Water depths of up to 2500 m are postulated in West Timor and parts of East Timor during the time intervals 5.7–5.5 Ma and 5.5–4.3 Ma, shallowing to 500–1500 m, as the island emerged between 4.3 and 3.3 Ma. The emergence of Timor Island led to major changes in oceanic circulation patterns, meridional heat transport and paleoclimate changes (Linthout *et al.*, 1997; Cane & Molnar, 2001; Kuhnt *et al.*, 2004), especially modifications and restrictions to the Indonesian Throughflow (ITF).

Progressive collision

At present the Australian Plate is moving northwards at approximately 77 mm/year (Genrich *et al.*, 1996; Fig. 1). Several forearc sections of the collision appear to have accreted to the Australian Plate, as they have similar velocities and move in the same direction as the Australian Plate, although there may be some variation in rates (Nugroho *et al.*, 2009). With current trajectories and rates, it is likely that the Australian Plate will begin colliding with remnants of arc terranes and continental fragments of the Sunda Shelf in about 10 million years (Nugroho *et al.*, 2009). Such a collision could result in deformation and associated changes in orography, oceanography, climate and marine biota as currently evident in New Guinea, which is at an intermediate point of a similar collisional style (Nugroho *et al.*, 2009). Although there is some evidence of limited shortening continuing between Timor and Darwin (~20 mm/yr; Nugroho *et al.*, 2009), it is unlikely that the Timor Sea, through which waters of the Western Pacific Warm Pool (WPWP; Fig. 2) flow, will be drastically affected, as shortening deformation in the last three million years has largely been accommodated on large strike-slip faults and domal upwarping on Timor Island (Keep & Haig, 2010; Haig, 2012).

In the short term, as the Australian Plate progresses northwards, the main drivers of changes to oceanography and marine biota around the western and northwestern

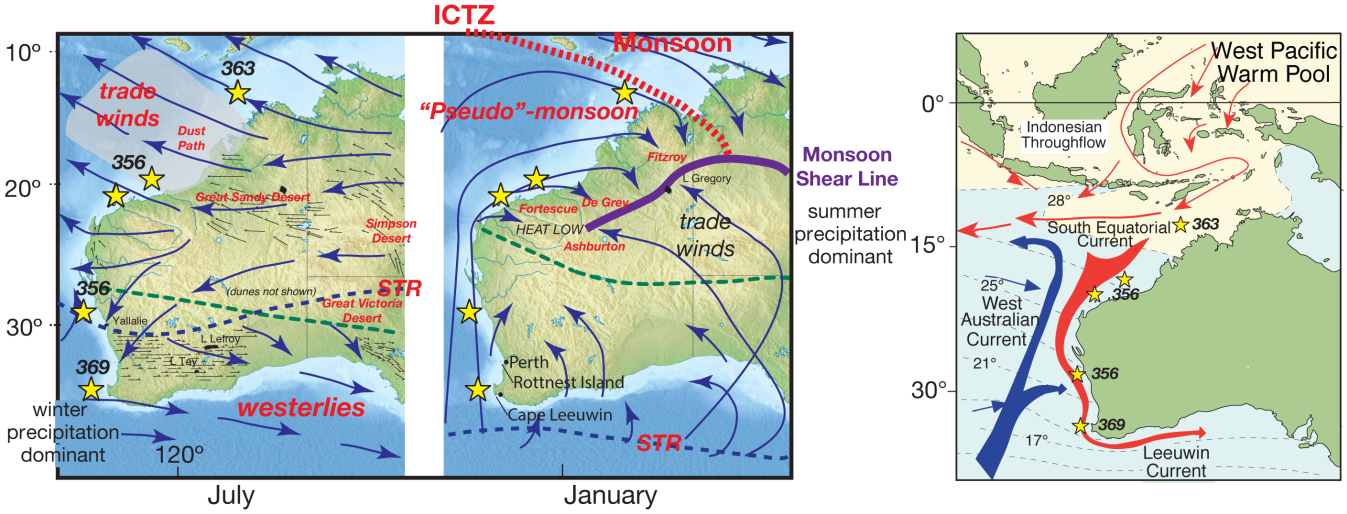

Figure 2. The climate and oceanographic setting of northwestern Australia. The average atmospheric circulation for January and July is adapted from Gentilli (1972) and Suppiah (1992) showing the mean position of monsoon shear line (McBride, 1986) and the Inter Tropical Convergence Zone (ICTZ). The dunefield map and dust path is from Hesse *et al.* (2004). The annular spatial variation in the Subtropical high pressure Ridge (STR) is from Timbal & Drosdowsky (2013). The oceanographic setting is based on Gallagher *et al.* (2009, 2014) showing mean annual sea surface isotherms. The stars denote three recent IODP expeditions discussed in the text (see also Fig. 4). The location of key terrestrial archives (lakes) are shown with the position of important monsoonal rivers.

Australian margin will be earthquake-induced disruptions. The present far field stress is oriented at ~ 110° (Hillis & Reynolds, 2003; Clark & Leonard, 2003; Revets *et al.*, 2009; Fig. 3), causing an overall right-lateral strike-slip strain field to affect large areas of western Australia, both onshore and offshore (Keep, 2013; Fig. 3). Manifest as a series of pull-apart basins both along the coast and into the interior of Western Australia (Keep *et al.*, 2012; Keep 2013), the stress field has also caused a large number of earthquakes (Leonard & Clark, 2011), both onshore and offshore, with dominantly strike-slip focal mechanisms (Revets *et al.*, 2009; Keep *et al.*, 2012). Since 1900 there have been 200 earthquakes exceeding magnitude 4 in offshore and adjacent onshore areas of the coastal margins, with M6.6 as the highest recorded in the region (Fig. 3; Geoscience Australia, 2018). If earthquakes less than M4 are included the number increases by many hundreds. These earthquakes form clusters around well-documented slide areas (e.g., the Gorgon, Bonaventure and Picard slides; Fig. 3), as well as other areas of known, but poorly documented, slide activity (Shark Bay slide area, Mermaid Fault; Fig. 3).

Both onshore and offshore these earthquakes have caused topographic scarps (Keep *et al.*, 2012; Keep, 2013) and surface-breaching faults associated with landslide activity, some of which have been captured in shallow seismic and in cores (Scarselli *et al.*, 2013; McCormack & McClay, 2013). A number of small landslide deposits were identified in the shallow offshore parts of the Carnarvon Basin during IODP 356 (Gallagher *et al.*, 2017; Fig. 3). These landslides, of geologically recent ages, have the ability to locally disrupt marine biota and seafloor geomorphology, as well as releasing gases.

(Paleo)climate and ocean (paleo)environmental archive of Western Australia

Over the last 65 million years, Earth's climate has experienced a major transition from Paleogene warmth (greenhouse) to Neogene ice ages (icehouse; Zachos *et al.*, 2001; 2008). Paleogene Earth was dominated by greenhouse conditions in the absence of permanent ice caps when atmospheric CO_2 levels ranged from 1000 to 2000 ppm (part per million; Beerling & Royer, 2011; Pagani *et al.*, 2005). About 34 million year ago, CO_2 in the atmosphere declined to between 400 and 600 ppm (Beerling & Royer, 2011; Pagani *et al.*, 2005; Pearson *et al.*, 2009) close to the modern range and that projected in 2100 (IPCC, 2014). This cooling culminated in the Antarctic Ice Sheet expansion and the onset of icehouse conditions (Zachos *et al.*, 2001; 2008). Understanding of the geological history of the Western Australian margin during major climate transitions and "modern-analogue" conditions is crucial if we are to project how the climate and ocean environment of Western Australia will evolve under conditions of enhanced greenhouse warming.

The thick sedimentary succession that accumulated over the last 65 million years off Western Australia includes subtropical to tropical shelf carbonate, and deep-water calcareous mudstone and siltstone incised by submarine canyons (Wallace *et al.*, 2002; 2003). In combination, these sediments comprise a progradational shelf sequence typical of the Australian continental margin (Wallace *et al.*, 2002).

The Cenozoic succession on the North West Shelf has been well-documented using industry well and seismic data. Progradational carbonate clinoforms initiated during the early Oligocene continuing into the Miocene

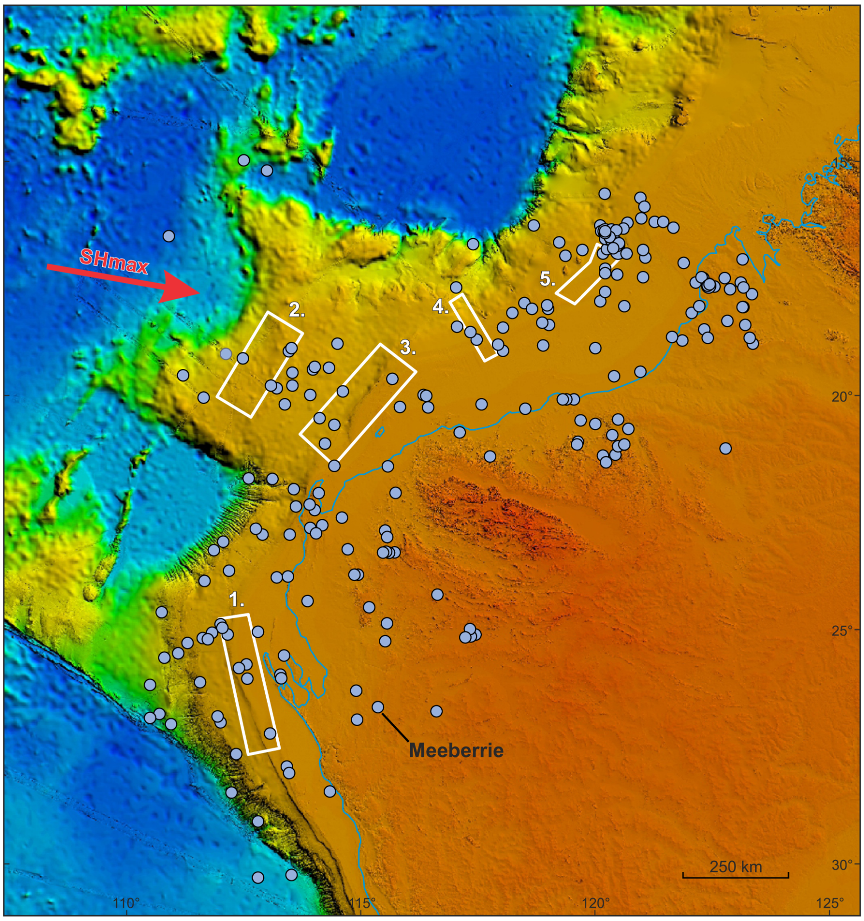

Figure 3. Seafloor bathymetry of Carnarvon Basin and surrounding areas, showing locations of all earthquakes >M4 in the offshore and adjacent onshore areas since 1900 (Geoscience Australia, 2018), shown as dots. The boxes represent areas of known landslide including: 1. Shark Bay Slide; 2. Bonaventure Slide; 3. Gorgon Slide; 4. Picard Slide; 5. Mermaid Fault area. Meeberrie was the location of Australia's largest recorded earthquake, M7.1, in 1941. The predominant orientation of current maximum horizontal stress (SHmax) shown in red is 110°. See Figure 1 for location of this region.

(Hull & Griffiths, 2002; Cathro *et al.*, 2003). Late early Oligocene–early late Miocene carbonates are heterozoan (i.e., derived from organisms that do not need light) and include benthic foraminifera with lesser bryozoans and minor coral fragments (Cathro *et al.*, 2003). The carbonate sediments developed on un-rimmed platforms in the absence of reefs. Evidence for pre-Quaternary reef development is limited; reefs or reef mounds are interpreted in the Oligocene–Miocene sections north of 22°S (Romine *et al.*, 1997; Cathro *et al.*, 2003; Ryan *et al.*, 2009; Liu *et al.*, 2011). Rare reefs are present in the Pliocene at 18°S (Ryan *et al.*, 2009). A major phase of reef growth commenced about 500 000 years ago at 22°S (Gallagher *et al.*, 2014), associated with the most southerly expansion of reefs around the Houtman Abrolhos at 28°S (Collins, 2002; Fig. 4).

Further to the south little is known about the Cenozoic evolution of the offshore shelf sequences south of Northwest Cape (Fig. 1). Most of these data are in unpublished petroleum completion reports. However, Collins *et al.* (1998) summarised the carbonate stratigraphy of the Perth Basin using the stratigraphy of petroleum wells to explain the environmental setting of the Houtman Abrolhos reefs (Fig. 4). Data from well cuttings suggest that marine carbonate sedimentation persisted from the late Cretaceous to present. During the Cenozoic a carbonate wedge developed in the Perth Basin, dominated by bryozoan foraminiferal molluscan carbonate sediments. The first reefal type facies occurs in the upper ~130 m (Pleistocene) of the Gun Island-1 well on the Pelseart Platform/Houtman Abrolhos reefs (Collins *et al.*, 1993; Fig. 4). Limited subsurface data reveal the transition from Eocene to Miocene cool-water carbonates to Quaternary warm water carbonates and ultimately reef development (and Leeuwin Current intensification) prior to 135 000 year ago (Collins *et al.*, 1998).

Evolution of the Indonesian Throughflow and the Leeuwin Current

The oceanography off Western Australia is strongly affected by the WPWP (Fig. 2), an area of warm surface waters with an average surface temperature of 28°C, covering the tropical western Pacific and eastern Indian oceans. The WPWP plays a major role in heat transport from low to high latitudes, and varies on a decadal scale due to the El Niño/Southern Oscillation (ENSO; de Garidel-Thoron *et al.*, 2005). WPWP intensity acts as a switch in the climatic system and it therefore a key driver of long- and short-term global climate change (e.g., Xu *et al.*, 2006). Climatic cooling since 15 Ma and an evolving tectonic configuration (plate collision) created boundary conditions similar to modern oceanic conditions in the Indo-Pacific region. The WPWP is tectonically restricted by the Indonesian archipelago (Fig. 2) and continues into the Indian Ocean via the ITF (Gordon, 2005). Today, ten

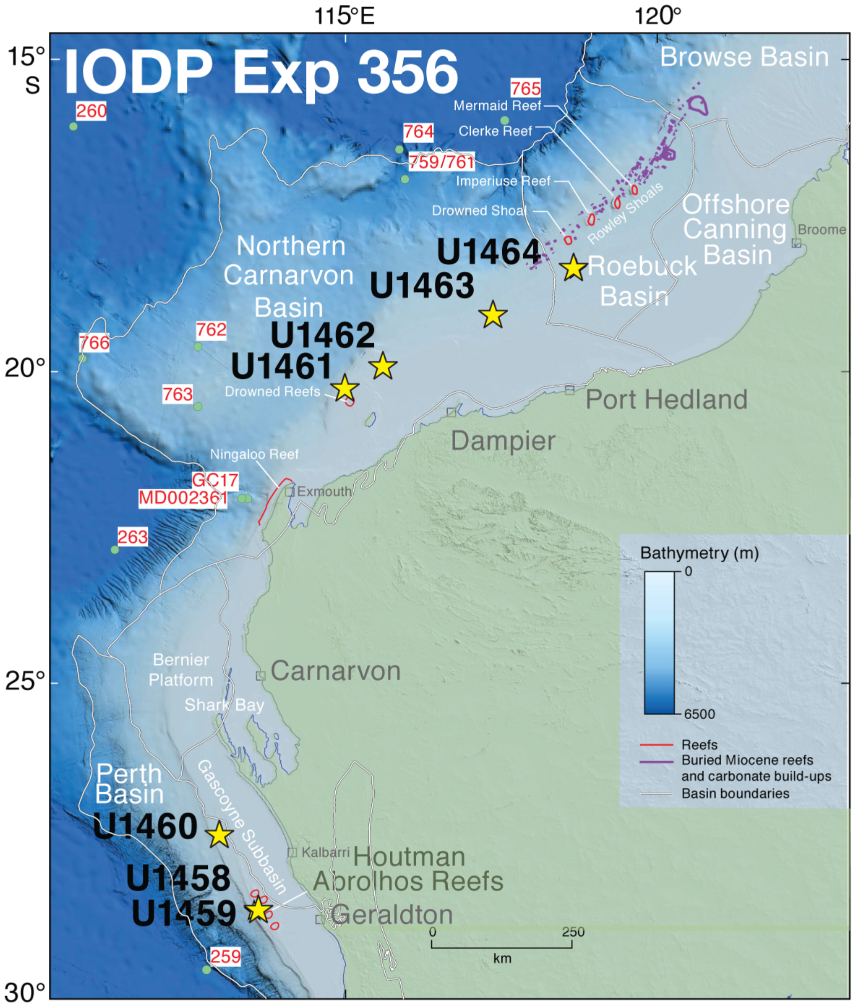

Figure 4. Map of the North West Shelf showing major basins and location of modern and "fossil" reefs. Stars = drill sites cored on IODP Expedition 356, green circles = DSDP/ODP sites and other core locations adapted from Gallagher *et al.* (2017)

to fifteen Sverdrups (1 Sv=106 m^3s^{-1}) of low salinity warm water are transported via the ITF into the Indian Ocean and the ITF acts as a key switching point in the global thermohaline conveyor.

The shelfal regions off Western Australia are strongly affected by shallow (50–300 m) currents sourced in the WPWP region. From 5°S to 15°S the oceanography is dominated by the South Equatorial Current (Collins, 2002). South of 15°S the shallow and narrow Leeuwin Current (<100 km wide; <300 m deep; Fig. 4) transports warm, low-salinity nutrient-deficient water southward along the west coast of Australia to Cape Leeuwin and into the Great Australian Bight (Pattiaratchi, 2006). This current is driven by longshore winds and an upper-ocean pressure gradient (upper 250–300 m; Tomczak & Godfrey, 1994) that overcomes equator-ward wind stress and upwelling to flow south (Pattiaratchi, 2006). The steric height difference between the low-density and -salinity Timor Sea and the cooler, denser, saline waters off the coast of Perth is also a major control on this current. The Leeuwin Current is the only south-flowing eastern boundary current in the Southern Hemisphere and strongly affects the climate of the region. Today, the current extends modern coral reef development to 29°S (the Houtman Abrolhos reefs; Collins *et al.*, 1993; Fig. 4) and the tropical–subtropical transition to Rottnest Island (33°S, Greenstein & Pandolfi, 2008; Fig. 2).

Whereas the late Pleistocene and modern oceanography of the Leeuwin Current is relatively well known (see Cresswell, 1991; Pearce, 2009, and references therein), its pre-Late Pleistocene history is poorly understood (Kendrick *et al.*, 1991; Wyrwoll *et al.*, 2009). The Leeuwin Current probably ceased during glacial periods and restarted during interglacials (James *et al.*, 1999). Fossil assemblages suggest that the Leeuwin Current initiated after 500 ka (Kendrick *et al.*, 1991). Other workers (Sinha *et al.*, 2006; Karas *et al.*, 2011) proposed an earlier onset at 2.5 Ma, and McGowran *et al.* (1997) indicated that it may have originated in the late Eocene (40 Ma). Foraminiferal biogeographic data suggest the "modern" Leeuwin Current commenced about one million years ago (Gallagher *et al.*, 2009; 2014). Stable isotopes and planktic foraminifera from a deep-sea core (MD00-2361, 1805 m water depth, ~70 km west of Northwest Cape; Fig. 1), which preserves a sedimentary record for the last 500 000 years, indicates a weaker Leeuwin Current during glacial times, when the West Australian Current dominated and a strong Leeuwin Current during interglacial periods (Spooner *et al.*, 2011).

The Australian monsoon and paleomonsoon climate

At present, the northwestern margin of Australia is influenced by strong summer westerly and southwesterly winds that source warm, moist equatorial air inducing monsoonal rains and cyclonic activity north of the monsoon shear line (at ~25–20°S, McBride, 1986). The resulting ephemeral runoff delivers a significant volume of fluvial siliciclastic sediment (clay/sand) to the region via the Fitzroy, De Grey, Ashburton and Fortescue rivers (Fig. 2). In contrast, continental eolian dust is transported to the North West Shelf, when the winds reverse during the winter dry season (Christiansen *et al.*, 2017; Fig. 2).

The geological history of the Australian monsoon and its record on the North West Shelf are primarily based on palaeorecords from cored strata younger than 500 000 years old. Nevertheless, Herold *et al.* (2011) and Greenwood *et al.* (2012) used fossil proxy data (palynology, palaeobotany) to model a seasonally wet northern and interior Australia during the Miocene (23 to 14 million years ago) consistent with a monsoonal precipitation regime wetter than today, but with a monsoonal front in a similar position (Gallagher *et al.*, 2017). Initial results from Expedition 356 (Fig. 4) have shown that natural gamma radiation spectra of %K, Th ppm and U ppm may be used as proxies for fluvial and eolian inputs to track the transition between arid and humid climates over the last 20 million years. Elemental records from Northern Carnarvon Basin Site U1463 (Christensen *et al.*, 2017) indicate an abrupt transition from a dry middle-late Miocene climate to a Humid Interval at ~5.5 Ma. Rainfall was probably year round until initiation of a Transitional Interval at ~3.3 Ma, after which it became more seasonal (Christensen *et al.*, 2017). Northward movement of Australia led to progressive ITF constriction, which decreased continental humidity, culminating in the Arid Interval, beginning at ~2.4 Ma, (Christensen *et al.*, 2017) when seasonal (monsoonal) and orbitally controlled precipitation were fully established. This transition coincided with intensification of the Northern Hemisphere glaciation at 2.73 Ma. The Plio-Pleistocene transition from humid to arid conditions may have been driven by changes in Pacific and Indian Ocean circulation and regional atmospheric moisture transport, influenced by the emerging Maritime Continent (Christensen *et al.*, 2017).

Evidence of an increasingly arid Western Australia during the Pleistocene is provided by the initiation and expansion of the dune field in the monsoon influenced Simpson Desert in central Australia about one million years ago (Fujioka *et al.*, 2009: Fujoika & Chappell, 2010; Fig. 2). Several later major drying events are recorded in eastern Australian lakes (Habeck-Fardy & Nanson, 2014; Fitzsimmons *et al.*, 2015). The shelfal sediments on the North West Shelf are predominantly carbonates; however, a variable siliciclastic component is also present. Previous work on sections near Barrow Island (Gallagher *et al.*, 2014; Fig. 1) revealed strong interglacial/glacial variations in clay input over the last two million years, whereby green clayey sand predominated during interglacial wetter conditions (related to a stronger monsoon) and carbonates (and minor siliciclastics) during the dryer glacial phases, as conditions became more arid. This work revealed that the apparent upward decrease in Australian monsoonal intensity over the last two million years was accompanied by increased alkalinity and carbonate supersaturation due to enhanced aridification of northwestern Australia (Gallagher *et al*., 2018). IODP Expeditions 356 and 363 have extended the siliciclastic record back to the Miocene (Gallagher *et al*., 2017; Rosenthal *et al*., 2017) yielding a 22° to 13° latitudinal palaeo-record of the Australian monsoon that is presently being researched and briefly described below.

A 100 kyr palynofloral climate archive west of the Cape Range Peninsula (Core GC17; van der Kaars & De Deckker, 2002; van der Kaars *et al*., 2006; Fig. 1) is representative of the most southern extent of the (present) Australian summer monsoon. Pollen transfer functions indicate a marked reduction in summer rainfall in the absence of monsoonal activity during the Last Glacial Maximum (van der Kaars *et al*., 2006). Other Quaternary monsoon archives are from further north in the Timor Sea (13°S, Holbourn *et al*., 2005; Kuhnt *et al*., 2015) and in the Banda Sea (5°S; Beaufort *et al*., 2010; 8.5°S, Spooner *et al*., 2005; Fig. 1). Holbourn *et al.* (2005) reconstructed Timor Sea palaeoproductivity over the last 350 ky, based on microfossil and geochemical proxies. Variations follow the 25°S summer insolation curve, suggesting a strong precessional and eccentricity control such that tropical and/or Southern Hemisphere insolation forcing was a modulating factor for Australian monsoon intensity. A recent study over the last glacial termination showed that the development of the Australian monsoon closely followed the deglacial warming history of Antarctica (Kuhnt *et al*., 2015). X-ray fluorescence scanner elemental data in four well-dated sediment cores, forming a NE–SW transect across the Timor Sea, document a massive intensification of the monsoon coinciding with Southern Hemisphere warming and intensified greenhouse forcing over Australia following the Antarctic Cold Reversal (15–12.9 ka). Therefore, monsoon intensification and the southward shift of the ITCZ coincided with the main deglacial atmospheric CO_2 rise at 12.9–10 ka. A return to dryer conditions between 8.1 and 7.3 ka followed maximum runoff in the early Holocene.

Overall, the Pleistocene Australian monsoon exhibit a strong glacial–interglacial variability (Wyrwoll & Miller, 2001). Marked changes in Australian monsoonal strength between interglacial and glacial periods (paced by precession and eccentricity) over the last 460 ky documented off northwestern Australia (Kawamura *et al*., 2006) show enhanced monsoonal (wet) conditions during interglacial periods and a weaker monsoon (dry) during glacials. This type of glacial–interglacial rainfall variability is also interpreted in a 550 ky dust record just off North West Cape (Stuut *et al*., 2014). In terrestrial records, significant river runoff and megalake expansion in northern and central Australia (Hesse *et al*., 2004) typified interglacials over the last 300 000 years due to an enhanced Australian monsoon. In contrast, weaker monsoonal activity led to a decline in rainfall (van der Kaars *et al*., 2006) and megalake drying during glacial conditions (Magee *et al*., 2004) across the region (~23°S).

The westerlies south of 26°S

Strong westerly winds dominate the mid latitude regions south of 26°S on the western margin of Australia. The north–south movement of the westerlies forms part of the Southern Annular Mode (SAM) and results in significant seasonal precipitation changes (wet winter, dry summer) in the southern half of Australia (Marshall, 2003; McLaren *et al.*, 2014; Groeneveld *et al.*, 2017). SAM is the variance between the normal monthly zonal mean sea level pressure at 40°S and 65°S (Marshall, 2003). When SAM increases the Southern Hemisphere Westerlies migrate northward causing winter precipitation (Marshall, 2003; Groeneveld *et al.*, 2017).

Compared to northwestern Australian, little is known about the long-term climate evolution in the southwest. Sand dunes and dust pathways can be used as indicators of past wind strength and the relative strength of the westerly wind belt (Hesse *et al.*, 2004). During the LGM (Last Glacial Maximum), this eolian evidence suggested a minor northward shift (3°) of the westerlies, returning to their present position during the Holocene. Nevertheless, winds were no stronger than present during the LGM (Hesse & McTainsh, 2003; Hesse *et al.*, 2004) with similar directions to today. Older records of the regional climate from extensive palaeodrainage systems and limited floral records (Clarke, 1994, Martin, 2006) indicate wetter Eocene to Oligocene conditions. However, a trend to more arid conditions is suggested by the cessation of major river systems by the Middle Miocene (van der Graff *et al.*, 1977). Floral fossils at Lake Tay (Dodson & Ramrath, 2001) and Yallalie (Dodson & MacPhail, 2004; Fig. 2) indicate a wetter climate compared to today in southwest Australia during the early Pliocene. Increasing aridity in the late Pliocene and middle Pleistocene led to the drying out of lakes and gypsiferous evaporitic deposits (e.g., Lake Lefroy, Clarke, 1994; Zheng *et al.*, 1998, 2002).

NEW OCEAN AND CLIMATE ARCHIVES FROM IODP EXPEDITIONS AND RV "*SONNE*" RESEARCH CRUISES OFF WESTERN AUSTRALIA

A potentially significant archive of Cenozoic climate and oceanic variability is preserved in sedimentary basins and shelf sequences along the offshore and onshore coastal regions of northwestern Australia. The thickest and most complete archives (up to two km thick) are preserved offshore (Longley *et al.*, 2002). However, to date these offshore archives have been sparsely sampled (by drilling) during hydrocarbon exploration and have primarily been interpreted using industry seismic data (Longley *et al.*, 2002). Recent coring by the IODP has obtained high resolution Paleogene to Neogene climate and environmental records along a latitudinal transect from 13°S to 34°S (Fig. 2). This transect includes Expedition 363 over 13–15°S (Rosenthal *et al.*, 2017); Expedition 356 over 18–29°S (Christiansen *et al.*, 2017; Gallagher *et al.*, 2017; Groeneveld *et al.*, 2017); and Expedition 369 over 33–34°S (Huber *et al.*, 2018). The research potential of these new archives is discussed below.

IODP Expedition 356

IODP Expedition 356 (Fig. 2) cored several sections to investigate the latitudinal variation in climate and ocean conditions from ~29°S to 18°S over the last five million years (Gallagher *et al.*, 2017). The sites were located to provide insights into reef development and the Leeuwin Current history. They were positioned relatively close to the shoreline in order to preserve eolian and fluvial derived siliciclastics, and spores and pollen to determine the long-term history of the Australian monsoon and southwestern Australian climate. Fortuitously, most sites yielded older strata revealing an archive of climate conditions going back to ~50 Ma, significantly older than the Pliocene sequences that were the main focus of Expedition 356. In the Perth Basin, Site U1459 at ~29°S, cored an Eocene to recent archive and Site U1460 (22.5° south) yielded a fully cored >200 m thick record for the last five million years. Both records have the potential to greatly enhance the limited climate records in the onshore southwestern part of Australia. Further north in the Carnarvon Basin (Fig. 1) Sites U1461, U1462 and U1463 at ~22°S yielded thick (up to 1 km) sections of late Miocene to recent strata that will reveal the southerly extent of the Australian monsoon and its intensity. In the Roebuck Basin Site U1464 at ~18°S drilled a middle Miocene to recent section with highly contrasting facies ranging from Miocene subaerial sabkha evaporitic facies (Groeneveld *et al.*, 2017; Tagliaro *et al.*, 2018) through Pliocene deep water tropical carbonates (Gallagher *et al.*, 2017; De Vleeshouwer *et al.*, 2018) to Quaternary tropical shallow shelf oolites at site 1462 (Gallagher *et al.*, 2018). These Carnarvon Basin cores, when combined with section cored further north during IODP Expedition 363 (see below), provide an unprecedented opportunity to investigate the long-term history of the monsoon, aridity and oceanography in northwestern Australia.

Recent work by Groeneveld *et al.* (2017) on two IODP Expedition 356 sites (Sites U1464 and U1459, Fig. 4) on the North West and Rottnest shelves has revealed a window into Western Australian climate variability from 18 to 6 million years ago. During this period, the Australian continent was 5° to 10° further south than today, and southwest Australia was influenced by the westerlies. Continued northward movement of the region out of this airflow potentially increased aridity. However, the palaeoclimate record is not as straightforward. Various proxies show that Western Australia was arid from 18 to 11 million years ago. While southwest Australia became wetter after 11 million years ago, creating a climate gradient with the arid interior, northwestern Australia continued to remain arid during this time. Rainfall and fluvial runoff in southwest Australia gradually increased between 12 and 8 Ma, possibly related to the northward migration or intensification of the westerlies. The westerlies moved back to south of Australia about eight million years ago causing aridification.

IODP Expedition 363

IODP Expedition 363 sought to document climate variability in the WPWP from the middle Miocene to late Pleistocene on millennial, orbital and geological timescales (Rosenthal *et al.*, 2017). Nine sites were cored (two off northwestern Australia and seven in the heart of the WPWP) in water depths ranging from 875 to 3421 m from which 6956 m of sediment cores were recovered. Sites U1482 (1466 m water depth) and U1483 (1733 m water depth) lie seaward of the continental slope of northwestern Australia at the southwestern edge of the WPWP and along the main exit of the ITF into the Indian Ocean (Fig. 1). Both of the latter sites are within the hydrographic transition that separates warm tropical waters from subtropical water masses and are close to the oceanographic front between relatively cool, nutrient-rich water carried northward in the Eastern Indian Ocean by the West Australian Current and warm, oligotrophic Leeuwin Current waters (Rosenthal *et al.*, 2017). The location of these two sites along the main exit path of the ITF through the Timor Strait between Australia and Java (Fig. 1) is also ideal to monitor changes in the intensity and thermal structure of ITF water masses entering the Eastern Indian Ocean (e.g., Xu *et al.*, 2008). This area, at the southern edge of the largest amplitude seasonal swing of the Inter-Tropical Convergence Zone, receives monsoonal terrestrial runoff from the extensive river systems discharging from the central part of the Australian monsoon region. Thus, the continuous, extended upper Miocene to recent hemipelagic successions recovered at Sites U1482 and U1483 provide exceptional archives to reconstruct the climate and circulation history at the southwestern edge of the IPWP from the late Miocene to present.

IODP Expedition 369

While primarily focusing on Cretaceous ocean and climate (Huber *et al.*, 2018), IODP Expedition 369 also cored two Cenozoic ocean/climate archives near 34°S off Cape Leeuwin (Fig. 2). Site U1516 yielded >200 m of continuous core of Miocene–Recent carbonates and Site U1514 continuously cored >250 m of early Eocene to recent strata. Future research on these two key sections will yield the early oceanographic history of the Australian southern margin and its evolution as the continent migrated northward over 20° palaeolatitude. The cored sections have the potential to preserve wind-blown spores pollen and dust; studying these proxies will allow investigations of the long-term climate history of Australia's southwest margin.

RV "*Sonne*" cruises SO185 (VITAL) and SO257 (WACHEIO)

Whereas sedimentation on the NW Australian shelf is strongly influenced by tectonic subsidence and the availability of accommodation space, sedimentation in the bathyal zone (water depths from ~500 to 3000 m) is mainly controlled by a complex balance between terrigenous sediment supply across the shelf, autochthonous production of biogenic sediment and lateral advection of sediment by surface and bottom currents. Therefore, cores along transects seaward of Australia's shelf edge provide an opportunity to better understand the oceanic sediment transport and depositional systems. One of the main difficulties in high-resolution climate reconstructions for offshore

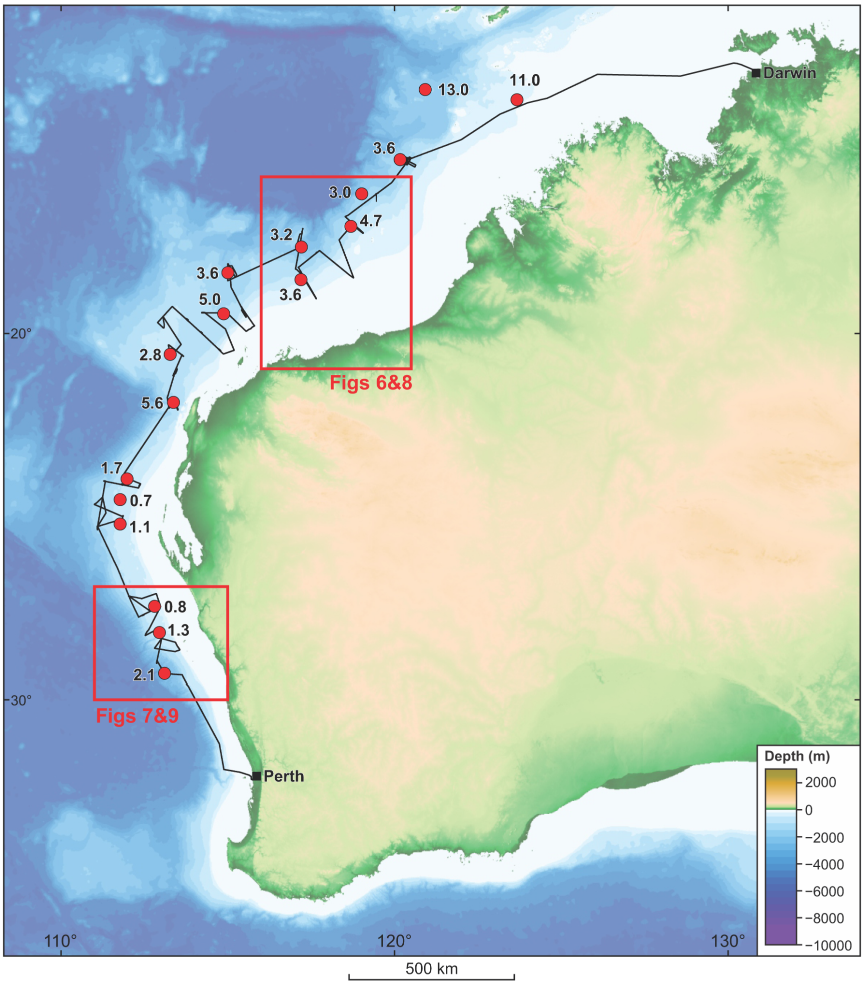

Figure 5. Average sedimentation rates (in cm/kyr) over the last 140 000 years (Recent to Marine Isotope Stage 6) along the NW Australian Margin in water depths of 500–3500 m, based on correlation of published oxygen isotope stratigraphy (Holbourn *et al.*, 2005; Stuut *et al.*, 2014) oxygen isotope and unpublished shipboard colour spectrophotometer data from R/V Marion Dufresne cruise MD122 (WEPAMA) and R/V *Sonne* cruises SO185 (VITAL) and SO257 (WACHEIO). Solid line is the 2017 ship track for the Sonne 257 cruise.

Table 1
Core locations and Holocene – Last Glacial Termination sedimentation rates off western and northwestern Australia (sedimentation rates for cores described in Wells and Wells (1994) are averaged over the entire last glacial cycle). Note that sedimentation rates based on Marion-Dufresne Calypso cores are significantly overestimated due to the oversampling of sediment in the uppermost 6 m of the Calypso-Coring system.

Location	Latitude	Longitude	Depth	Sediment rate	References
Scott Plateau – Rowley Terrace					
FR2-96-17	12°14.80'S	112°44.27'E	2571 m	2.5 cm/kyr	Takahashi & Okada (2000)
V28-342	14°06'S	120°30'E	2730 m	2.75 cm/kyr	Wells & Wells (1994)
SO08-14802	16°08.77S	118°15.93'E	5025 m	—	Von Stackelberg *et al.* (1979)
SO08-14805	16°21'S	118°23'E	2777 m	1.8 cm/kyr	Hesse & Stolz (1999) Hesse & McTainsh (2003)
SO08-14806	16°35.9'S	118°30.0'E	2060 m	—	Von Stackelberg *et al.* (1979)
SO08-14809	16°55.0'S	117°33.3'E	3800 m	—	Von Stackelberg *et al.* (1979)
ODP122-760A	16°55.32'S	115°32.48'E	1970 m	1.33 cm/kyr	Wells & Wells (1994)
SO08-14812	16°56.1'S	115°11.50'E	1600 m	—	Von Stackelberg *et al.* (1979)
SO08-14807	16°56.15'S	118°50.50'E	1186 m	3.5-8.0 cm/kyr	Zahn (1982) Hesse & McTainsh (2003) Sarnthein *et al.* (1982)
SO08-14810	17°12.8'S	115°19.6'E	3210 m	2.0 cm/kyr	Zahn (1982)
V28-345	17°40'S	117°57'E	1904 m	3.9 cm/kyr	Wells & Wells (1994)
Exmouth Plateau					
RS53-GC07	18°54.5'S	112°37.9'E	2256 m	2.4 cm/kyr	McCorkle *et al.* (1998)
RC11-147	19°03'S	112°45'E	1953 m	~2 cm/kyr	Kolla & Biscaye (1977) Wells & Wells (1994) Hesse & McTainsh (2003)
RS53-GC06	19°03.2'S	112°45.1'E	1979 m	1.7 cm/kyr	McCorkle *et al.* (1998)
ODP122-762B	19°53.24'S	112°15.24'E	1360 m	1.46 cm/kyr	Wells & Wells (1994)
RS53-GC04	19°35.1'S	113°32.1'E	956 m	2.2 cm/kyr	McCorkle *et al.* (1998)
RS53-GC09	20°00.3'S	112°55.9'E	962 m	2.6 cm/kyr	McCorkle *et al.* (1998)
SO08-14819	20°15.6'S	114°32.2'E	1075 m	—	Von Stackelberg *et al.* (1979)
SO08-14815	20°18.5'S	112°56.6'S	815 m	1.4 cm/kyr	Hesse & McTainsh (2003)
SO08-14820	20°45.5'S	114°02.4'E	1027 m	—	Von Stackelberg *et al.* (1979)
RS53-GC11	20°53.7'S	112°20.0'E	1432 m	1.5 cm/kyr	McCorkle *et al.* (1998)
SO08-14821	20°56.0'S	114°20.0'E	498 m	—	Von Stackelberg *et al.* (1979)
SO08-14824	21°07.4'S	112°46.4'E	1493 m	—	Von Stackelberg *et al.* (1979)
Carnarvon Terrace – Wallaby Plateau					
FR10/95-17	22°07.74'S	113°30.11'E	1093 m	6.7 cm/kyr	Takahashi & Okada (2000) van der Kaars & De Deckker (2003)
MD2361	22°04.92'S	113°28.63'E	1805 m	10.5 cm/kyr	Spooner *et al* (2011)
V33-65	22°44'S	112°35'E	1692 m	1.03 cm/kyr	Wells & Wells (1994)
RS96GC21	23°46.33'S	108°30.04'E	2100 m	0.83 cm/kyr	Wells & Wells (1994)
FR10-95-20	24°44.67'S	111°49.75'E	841 m	1.0 cm/kyr	Takahashi & Okada (2000)
RCI 1-145	25°29'S	110°01'E	3911 m	0.96 cm/kyr	Wells & Wells (1994)
Perth Basin					
RS57-GC19	27°19.2'S	111°37.6'E	2755 m	1.8 cm/kyr	McCorkle *et al.* (1998)
RS57-GC15	29°22.9'S	113°13.0'E	2750 m	1.2 cm/kyr	McCorkle *et al.* (1998)
RC9-150	31°17'S	114°33.1'E	2703 m	2.17 cm/kyr	Bé & Duplessy (1976) Wells & Wells (1994)
E45-102	33°37'S	113°35'E	1980 m	0.75 cm/kyr	Wells & Wells (1994)

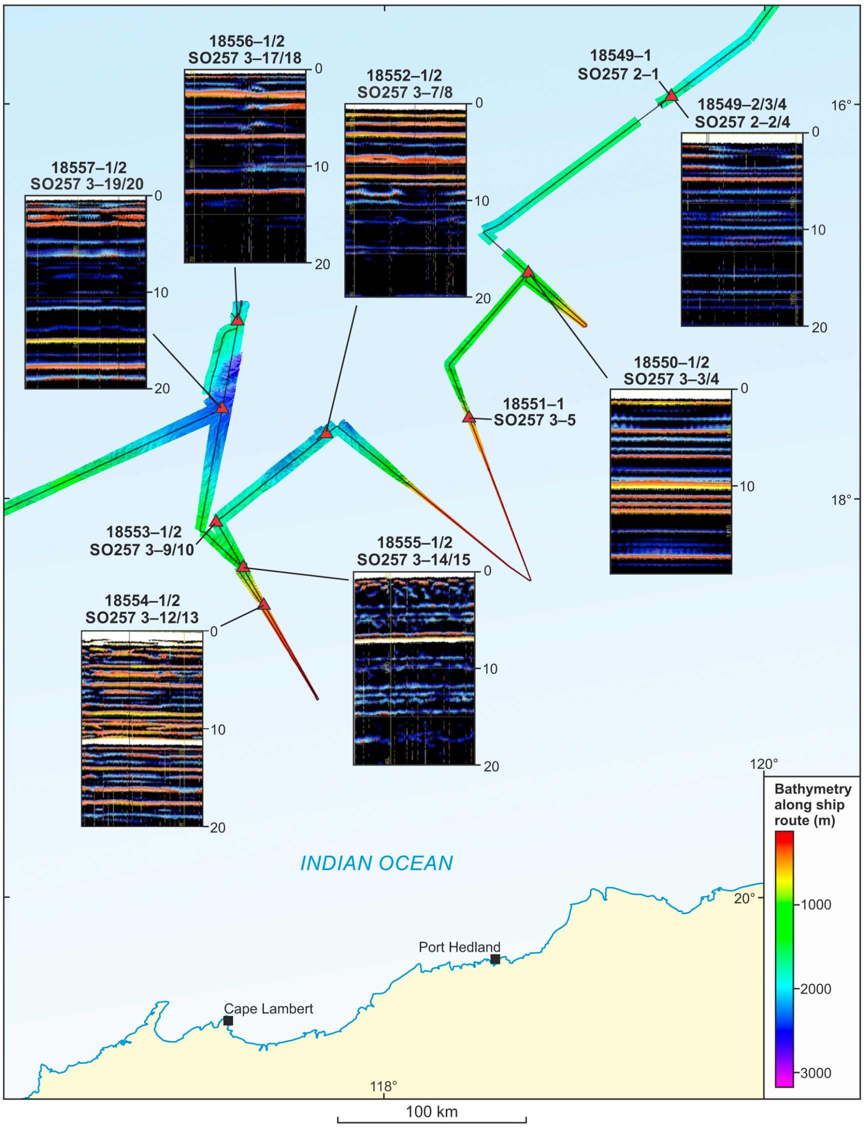

Figure 6. Acoustic character of bathyal sediment along the northwestern Australian margin (Parasound recordings at coring stations). Horizons with high acoustic impedance (light colours in parasound records) are characteristic for carbonate-rich sedimentation.

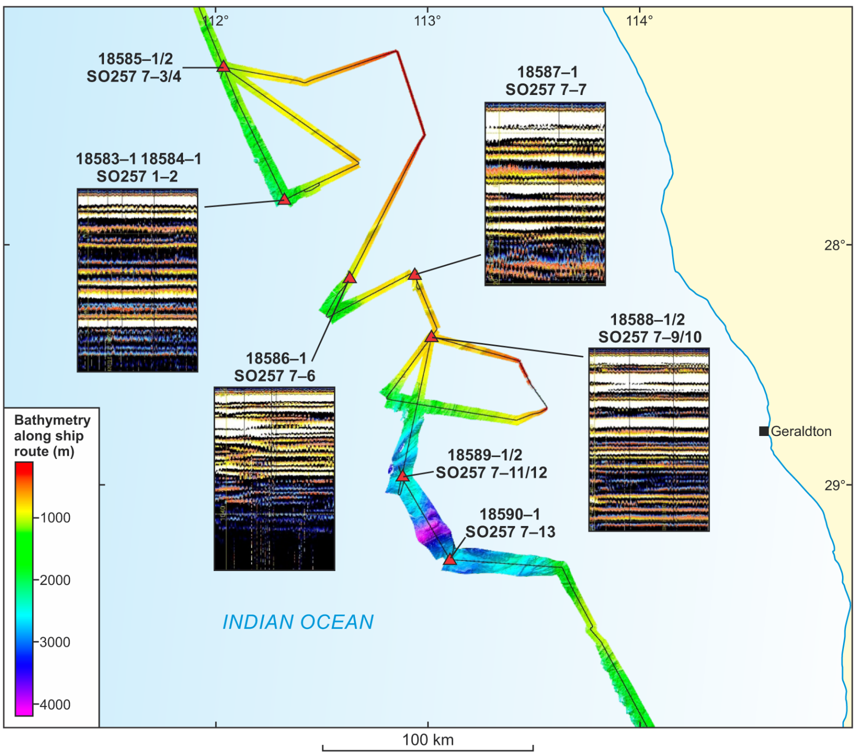

Figure 7. Acoustic character of bathyal sediment along the western Australian margin (Parasound recordings at coring stations). Dominance of light reflectors indicates the absence of clay-rich sediments.

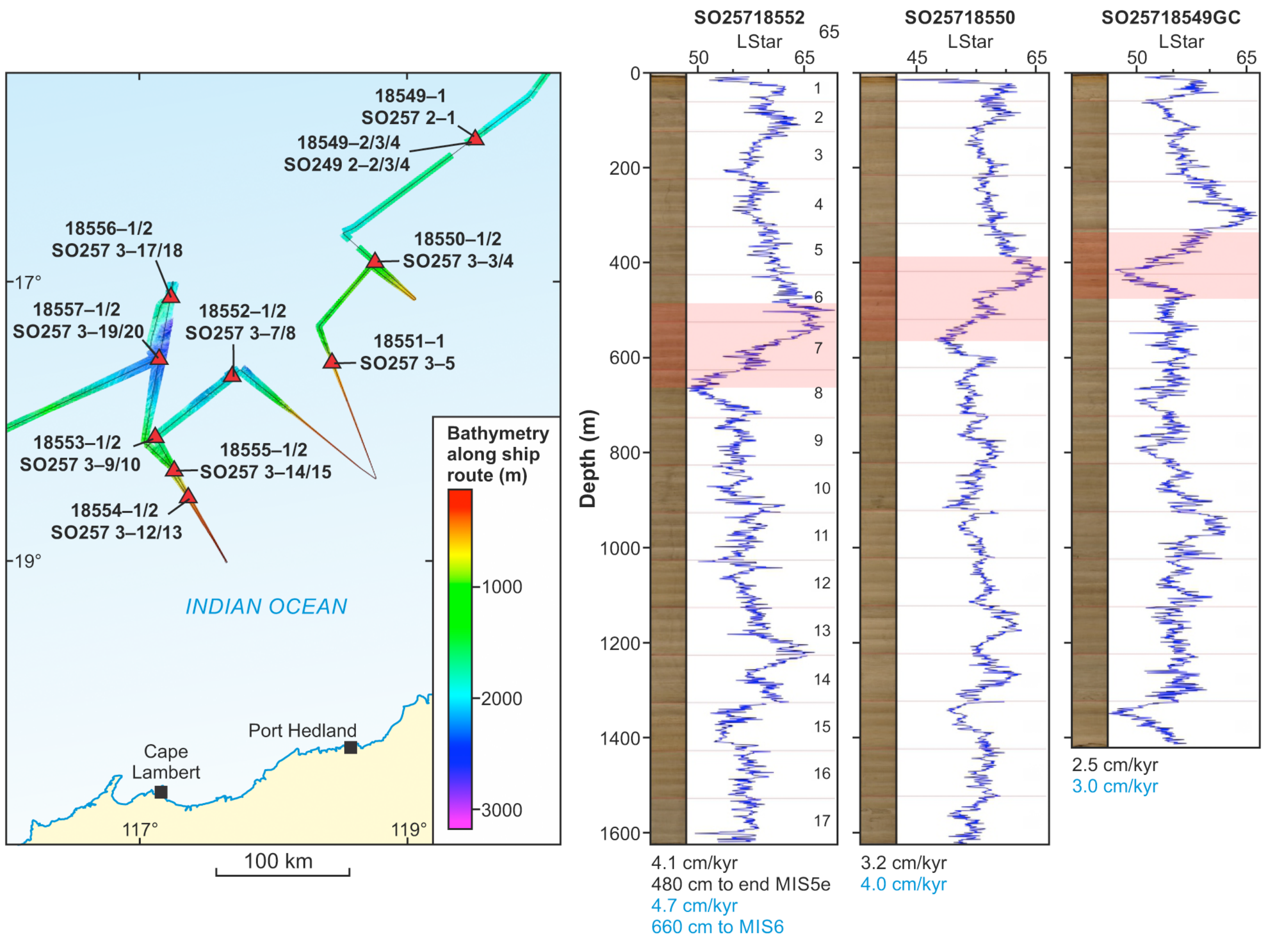

Figure 8. Typical bathyal sediment cores along the northwestern Australian margin. Sediment lightness (L-Star) values indicate carbonate-rich sedimentation. Prominent increase in carbonate content during Termination II towards a prominent maximum in early MIS 5e is marked by red shading).

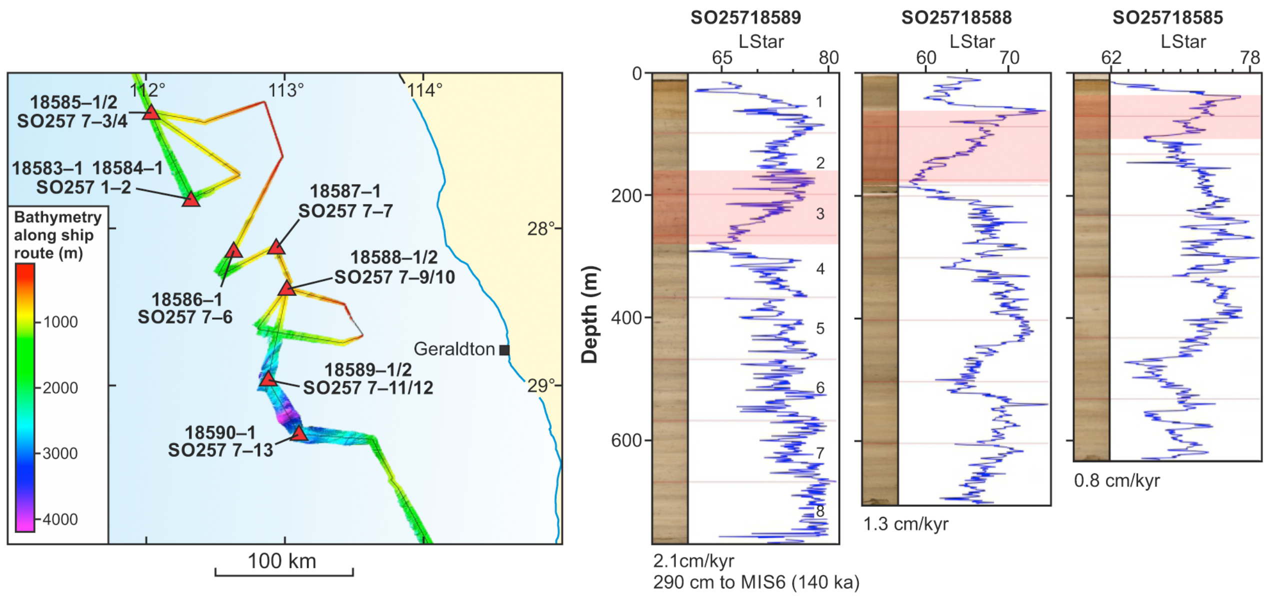

Figure 9. Typical bathyal sediment cores along the northwestern Australian margin. Sediment lightness (L-Star) values indicate carbonate-rich sedimentation. Prominent increase in carbonate content during Termination II towards a prominent maximum in early MIS 5e is marked by red shading).

Western Australia stems from a distinct NE–SW decrease in late Pleistocene–Holocene sedimentation rates along the NW and Western Australian margins (Fig. 5; Table 1). This trend has been explained by decreasing tectonic subsidence with distance from the northern Australian plate margin in conjunction with decreasing monsoon derived riverine sediment (Gingele & DeDeckker, 2004; De Deckker *et al.*, 2014).

Sediment cores recently recovered by the R/V *Sonne* cruise SO185 (VITAL) and SO257 (WACHEIO) indicate sedimentation rates and clay accumulation in the northernmost part of the northwestern Australian margin, north of the Scott Plateau, exceeded 10 cm/kyr during the late Pleistocene–Holocene (Kuhnt *et al.*, 2006, 2018; Fig. 5). In contrast, the margin along the Rowley Terrace between the Scott Plateau and Exmouth Plateau is characterized by intermediate sedimentation rates ranging between 2.8 and 5.0 cm/kyr with the exception of a small area ~40 nm NW of IODP Site U1462, where exceptionally high Holocene and Late Pleistocene sedimentation rates of more than 50 cm/kyr were encountered, probably representing a local sediment drift. Sedimentation rates also increase in a relatively small area at the SE edge of the Wallaby Plateau. There, a previous expedition recorded late Pleistocene–Holocene sedimentation rates of 6.7 cm/kyr in the upper to middle bathyal zone (Takahashi & Okada, 2000; van der Kaars & De Deckker, 2003) and 10.5 cm/kyr in the middle lower bathyal (Spooner *et al.*, 2001; Stuut *et al.*, 2014). South of the Exmouth Peninsula, sedimentation rates never exceed 2 cm/kyr, and show a tendency to increase basinwards. A typical rate of 2.1 cm/kyr was recorded in the lower bathyal core SO-257-18589 (Kuhnt *et al.*, 2018, Figs 6–9).

We discriminate three factors, which in conjunction control this distinctive pattern of sediment accumulation: (1) primary production of planktic carbonate (2) riverine runoff of terrigenous clay from Australian rivers during the monsoon/cyclone season, and (3) along-slope advection of clay by the near-surface Leeuwin current and associated deep water countercurrents (Gingele *et al.*, 2001a, b). The influence of relative sea-level and regional subsidence on these controlling factors appears of limited extent, since even during the extreme glacial–interglacial sea-level changes the general sedimentation patterns did not fundamentally change. This is in stark contrast to the sedimentation patterns on the shelf, where the creation of accommodation space in locally subsiding sub-basins played a major role in shaping regional sedimentation patterns (Gallagher *et al.*, 2017).

CONCLUSIONS

Australia's northward migration during the last 50 million years has allowed it to accumulate sedimentary sequences around its offshore margins from which changing climatic conditions can be evaluated. Uplift of islands in the Indonesian archipelago and the Papua New Guinea highlands, which progressed transitionally from east to west over the last 25 million years, has blocked the oceanographic interchange between the Indian and Pacific Oceans and created the near "modern" oceanography of the region with the onset of the ITF and related Leeuwin Current. Plate collision has likely narrowed the Indonesian gateway, which provides a major pathway for ITF waters originating from the WPWP. Ongoing tectonism causes anomalous earthquake activity in the region, which appears to be spatially linked to a number of large landslides, for which ages can be determined from biostratigraphic dating of their basal layers. However, over the next few million years, earthquakes landslides and related wave activity could destroy the sediment archives and disrupt global thermal circulation. Future research on key sections recovered by recent IODP Expeditions and research cruises will unravel the early oceanographic history of the Australian northwestern margin and its evolution as the continent migrated northward over 20° palaeolatitude. The new marine archives from this region also have the potential to preserve wind-blown spores, pollen and dust, thereby providing proxies for reconstructing the long-term climate history of Australia's northwestern margin.

ACKNOWLEDGEMENTS

S.J.G. and A.H. thank the International Ocean Discovery Program and USIO staff and the SIEM Offshore crew for their invaluable assistance and skill during Expeditions 356 and 363. We thank Neville Exon for his support during preparation of Expedition 363 and for his help in obtaining permissions. Funding was provided by the Australian IODP office and the ARC Basins Genesis Hub (IH130200012) to S.J.G. Funding for the R/V *Sonne* expeditions SO185-VITAL and SO257-WACHEIO was provided by the German Federal Ministry of Education and Research (BMBF grants 03G0185A and 03G0257A) to W.K. We thank the handling editor Arthur Mory and the two reviewers Brad Opdyke and Jody Webster whose comments greatly improved the manuscript.

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