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Quaternary environments and monsoonal climate off northwest Australia: Palynological evidence from Ocean Drilling Program Site 765

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ABSTRACT

The bathyal Ocean Drilling Program Site 765 at 5725 m water depth, offshore northwest Australia at 16°S is directly under the influence of the Australian monsoon during the Austral summer and is the recipient of continental dust during the Austral winter. It is downstream of the Indonesian Throughflow, which is a major arm of the global thermohaline circulation. As such it is ideally situated to record the climate and oceanic consequences of Quaternary climate variability. Despite being over 400 km from northwest Australia, palynomorphs (pollen and spores) are relatively common in this section, sourced via aeolian (during the dry winter) and benthic transportation processes and sediment plumes (during the summer monsoon). Detailed palynological analyses of this flora in the upper part of this core reveals intermittent snap shots of environmental and climate change over the last 300 kyrs. Interglacial stages are interpreted to be characterised by palynomorph-rich turbidite and calcareous ooze deposition whereas palynomorph-poor slowly accumulating siliceous oozes (deposited below the Calcium Carbonate Compensation Depth) are present during glacials. The dominance of Poaceae sourced from the Australian mainland in interglacial periods suggests that vegetation during these periods was similar to today. Interglacial palynofloral assemblages suggest a more intense wet season (Australian monsoon) with higher rainfall that allowed more active erosion and deposition onto the shelf. The presence of Indonesian sourced pollen and fern spore taxa, as well as warm water dinoflagellate species suggest enhanced Leeuwin Current and monsoonal intensity during interglacials times. The youngest part of the core is dominated by siliceous ooze, likely deposited during the Last Glacial Maximum and the early Holocene. The lack of calcareous ooze near the top of the core is likely caused by Holocene to Recent erosive processes or core disturbance. The presence of common charcoal in all samples over the last 300 kyrs shows that fire was a constant feature of the landscape in northwest Australia prior to human occupation of the region 65,000 years ago.

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1. Introduction

Ocean Drilling Program (ODP) Site 765 (15°58.54'S, 117°34.49'E) was cored off northwestern Australia (Fig. 1) on the southern Argo Abyssal Plain at a water depth of 5725 m below the Calcium Carbonate Compensation Depth (Ludden et al., 1990). The Argo Abyssal Plain is north of the Exmouth Plateau and is bounded on the north by the Java-Timor Trench of the Banda-Sunda Arc. The uppermost sediment in the core are Quaternary to middle Miocene calcareous, siliciclastic turbidites and radiolarian oozes that Ludden et al.

(1990) and Gradstein et al. (1992) interpret to have been derived from submarine canyons that incised the northwestern margin of the Australian shelf. In particular, ODP Site 765 is immediately downslope of the Swan Canyon (Fig. 1c) and this submarine canyon is thought to be the transportation pathway for sediment from the monsoonal influenced North West Shelf of Australia onto the Argo Abyssal Plain (Simmons, 1992; McMinn and Martin, 1992, 1994). McMinn and Martin (1994: p.95) suggest that while the sediment at Site 765 may lack the high resolution of undisturbed deep-sea strata they yield "little evidence of large-scale reworking beyond the age of the previously deposited turbidite". Therefore, these authors interpret the mixed pollen assemblages at ODP Site 765 to preserve a "complete time interval between successive turbidity

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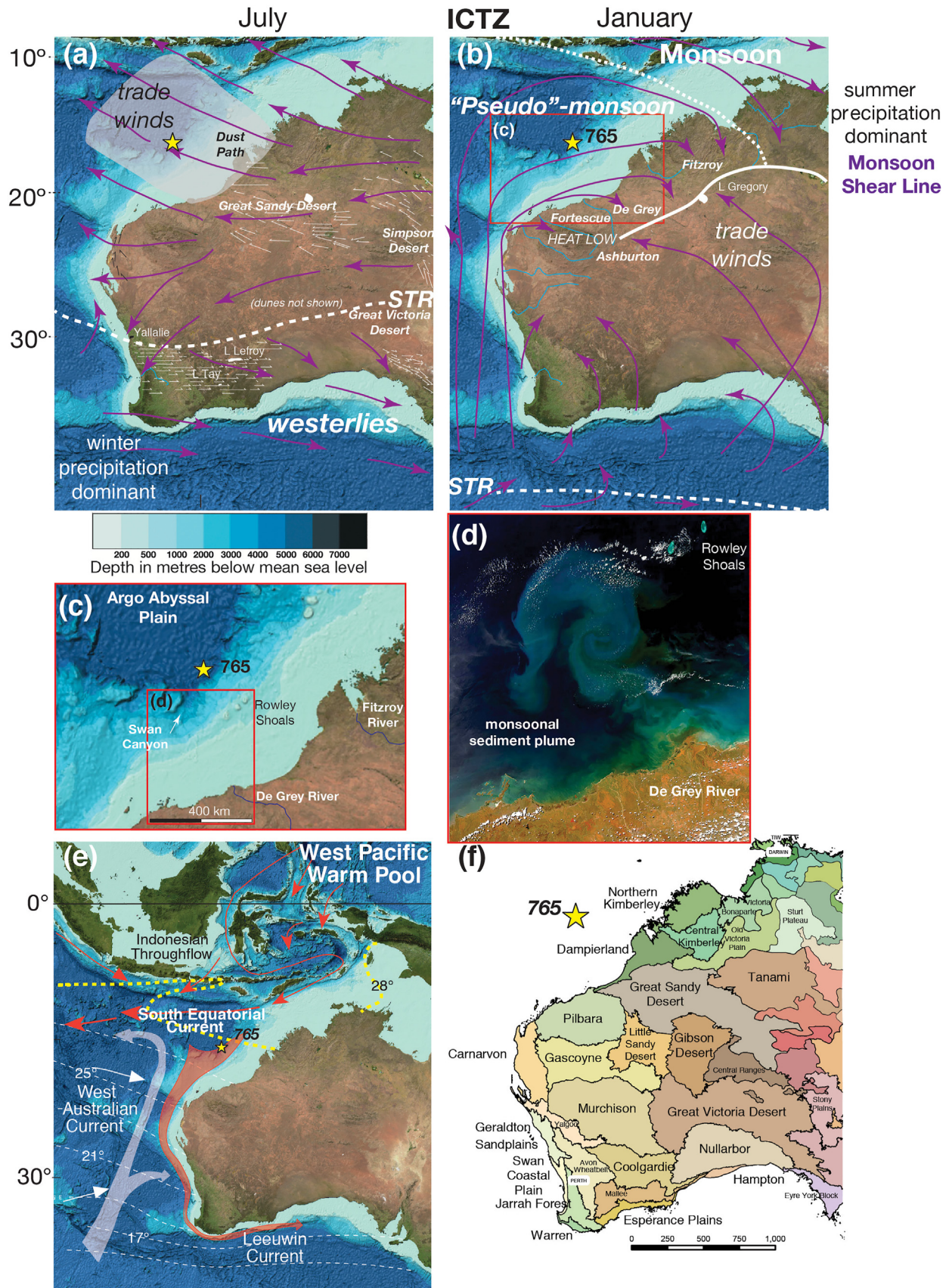


Fig. 1. Atmospheric circulation for (a) July and (b) January (Gentili, 1972) with the mean monsoon shear line (McBride, 1986) and Inter Tropical Convergence Zone (ICTZ). Base map adapted from General Bathymetric Chart of the Oceans (GEBCO) www.gebco.net with bathymetric contour intervals indicated. The yellow star is the location of ODP Site 765. The dune field map and dust path are adapted from Hesse et al. (2004). The annular spatial variation in the Subtropical high-pressure Ridge (STR) is from Timbal and Drosowsky (2013).

current flows" (McMinn and Martin, 1994, p.96). Low resolution palynological analyses on the youngest part of ODP Site 765 by McMinn and Martin (1992) outlined late Cenozoic palynomorph distribution and McMinn (1992) described Neogene dinoflagellate assemblages. However, the samples analysed in these two studies are widely spaced (44 samples covering 15 million years) and based on bulk samples (20 cm³), their purpose was to primarily to constrain the age of the strata with limited environmental interpretation. Other late Pleistocene to Recent palynological records in the region use marine surface sediments (van der Kaars and De Deckker, 2002, 2003) and deep-sea cores (Kershaw et al., 2003; van der Kaars et al. 2000, 2006; Wang et al., 1999) to interpret regional palaeoclimate. Hessler et al. (2013) used the present distribution of dinoflagellates as a proxy for ocean currents and water condition offshore north-west and west Australia using marine sea surface samples.

Northern Australia currently experiences a mild dry winter with moderate strength south-easterly trade winds (Fig. 1a) delivering continental aeolian dust to the region near ODP Site 765 (Hesse et al., 2004; Christensen et al., 2017). Moisture is generated during the summer monsoon (Fig. 1b) with these rains penetrating at least to 22°S (the monsoon shear line; McBride, 1986) and frequently further south (Suppiah, 1992). The present-day vegetation of the northern coastal regions of Western Australia is divided into a number of broad zones based on rainfall regime (Fig. 1f). The northernmost coastline is monsoon influenced and receives a summer rainfall of >900 mm (van der Kaars and De Deckker, 2003). The vegetation of the northern Kimberley region consists of monsoon rainforest, hummock grass (including spinifex) and *Eucalyptus* with *Melaleuca* paperbarks and pandanus along drainage lines. Inland from this region in the central Kimberley a hummock and ribbon grass understorey occur with pandanus, scattered trees and savannah. Moving south into Dampierland (Fig. 1f) *Melaleuca* grows along the coast with hummock grass and spinifex (*Triodia*) forming the understorey under scattered trees that increase in the riparian vegetation. The open woodland/savannah of the Pilbara consists of grasses (spinifex *Triodia*) with *Acacia* and *Eucalyptus*. Moving inland into the arid zone of the Great Sandy Desert (Fig. 1a), a tree savannah of open spaced hummock grasses, *Acacia*, Casuarinaceae and *Melaleuca* gives way to shrub steppe (Department of the Environment and Water Resources, 2007). Overall the vegetation that contributes to the pollen and spore flora at ODP Site 765 is likely sourced from the monsoon-influenced areas of northwest of Australia (Fig. 1b and c), where primarily eucalypts form open woodlands over grassy understorey, and the more open shrub land towards the south and inland, where *Acacia* increases. During the monsoon season spores/pollen are transported to the edge of the continental shelf (up to 400 km from shore) in cyclone related sediment plumes that originate from river outflow, likely from the De Grey River (Fig. 1c and d). It is not likely that this source is the Fitzroy River (Fig. 1c and d) as the sediment input to the shelf area is much further north. These sediments accumulate in the head of the Swan Canyon where slope processes transport them to the abyssal plain at ODP Site 765 (Simmons, 1992). Conversely, during the dry season, aeolian sourced pollen, spores and dust from northwest Australia (Fig. 1a) reaches ODP Site 765 (cf. Hesse et al., 2004).

The Northwest margin of Australia is strongly influenced by shallow (50–300 m) currents that originate in the West Pacific

Warm Pool (Fig. 1e, Gallagher et al., 2009; 2014; 2017). Regional oceanography from 5°S to 15°S 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) transports warm, low-salinity, nutrient-deficient water in a southerly direction along the west coast of Australia (Pattiaratchi, 2006). It is the only south-flowing eastern boundary current in the Southern Hemisphere and has a strong effect on the climate of the region. The Leeuwin Current extends modern coral reef development to 29°S (the Houtman-Abrolhos Reefs; Collins et al., 1993) and the tropical–subtropical transition as far south as Rottneest Island (33°S; Greenstein and Pandolfi, 2008).

The aim of this paper is to describe the terrestrial and marine palynological assemblages in the upper 12 m of ODP Site 765. These are compared to their modern equivalents and to interpret the palaeoenvironment and climate of the region over the last 300kyrs.

2. Materials and methods

Sixty 5 cm³ samples were taken from ODP Site 765 at an average sample interval of 0.2 m (Fig. 2). 3 cc of these samples were processed for palynology. The samples were deflocculated with 10% tetra sodium pyrophosphate and sieved at 125 µm to remove coarse sand and carbonate microfossils and at 7 µm to remove fine silt and clays. This was followed by 10% HCl, heavy liquid separation using sodium polytungstate (SG 2.0), HF and a safranin stain. The resultant residue was mounted in glycerol and sealed with paraffin wax. All samples were spiked with a known amount of *Lycopodium* marker spores prior to chemical treatment to allow palynomorph concentrations to be calculated. This is the processing method established by van der Kaars (2001) for marine core sediments; however, the acetolysis step was left out as it can remove thin walled dinoflagellates. Slides were examined using a Zeiss Axio Scope A1 microscope at ×400 magnification. Magnification of ×1000 and differential interference contrast (DIC) aided the identification of some angiosperm pollen and dinoflagellates. All transects on two slides were used to try and obtain a palynomorph count. All identifiable palynomorphs were used for totals and concentration calculations. Micro charcoal was also counted. In this study the poor recovery of palynomorphs made the plotting of individual taxa or percentage data of little value. Therefore, concentrations were calculated using the *Lycopodium* marker spores and taxa were grouped. The pollen diagram was created using WellPlot (Zippi 2009). Plant taxa that currently occur in the region onshore were determined using the Western Australian Herbarium website FloraBase (1998-).

3. Stratigraphy

The stratigraphy of the Quaternary strata of Site 765 B is outlined in Gradstein et al. (1992). We combine physical property data with original log sheet data from shipboard data (Ludden et al., 1990) to produce a detailed log of the upper 20 m of this core (Fig. 2). Metre-scale intervals of olive to dark greenish-grey siliceous (radiolarian) silt/mud alternate with greenish-grey and grey nannofossil sand/silt/mud. The tops of the siliceous intervals are typically scoured and overlain by centimeter-scale graded beds near the base of the overlying calcareous units. The overlying nannofossil mud is homogeneous with occasional upper

(c) Inset (red square) closeup of the bathymetry of Site 765 showing the position of the Swan Canyon. (d) Inset (red square) closeup of satellite imagery of a post cyclonic sediment plume from the mouth of the De Grey River that reached the Swan Canyon on the March 17, 2013 (from https://www.nasa.gov/mission_pages/hurricanes/news/rusty-sediment.html accessed August 3, 2020). (e) The oceanographic setting is based on Gallagher et al. (2009; 2014; 2017) showing mean annual sea surface isotherms and the 28 °C isotherm (yellow dashed line) defining the limit of the West Pacific Warm Pool. (f) A map of the biogeographic regions of Australia (IBRA, 2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

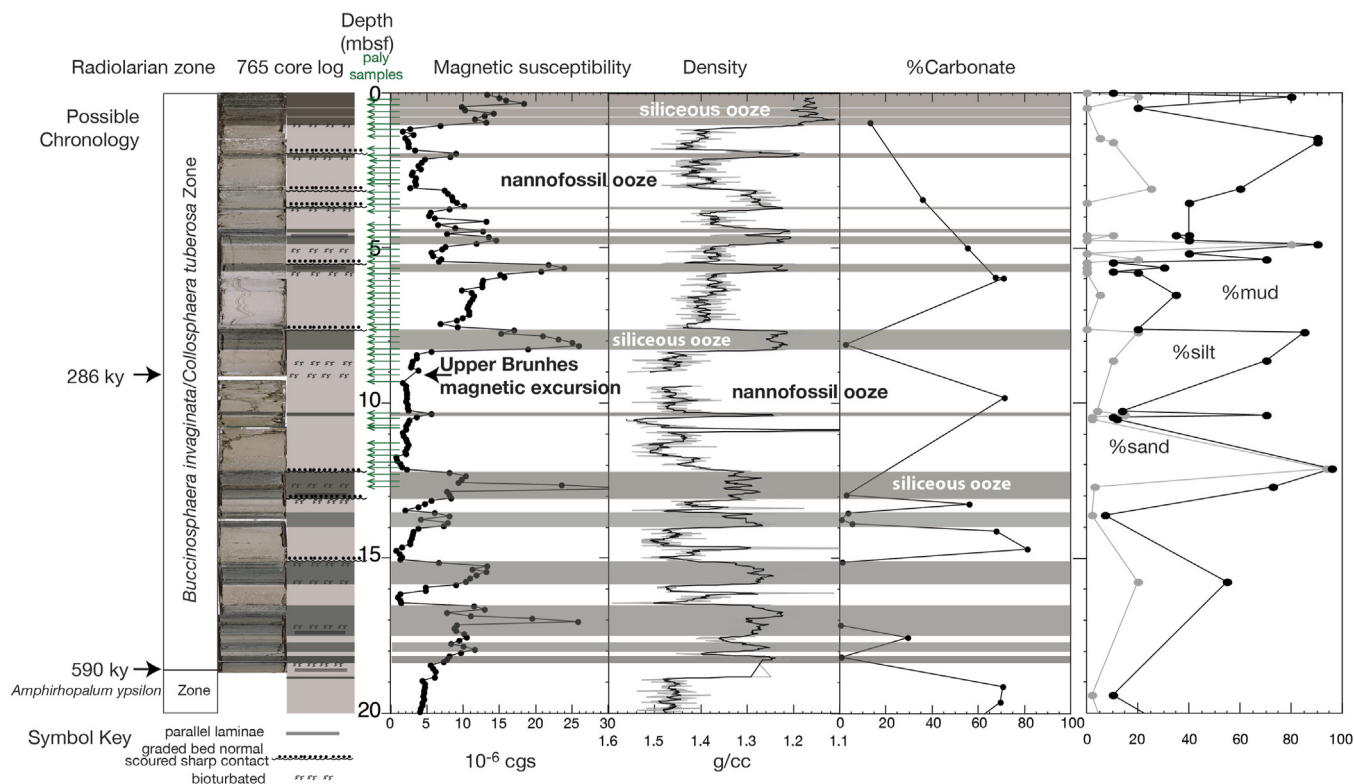


Fig. 2. The stratigraphy of the upper 20 m of ODP Site 765 B adapted from Ludden et al. (1990), Kaminski et al. (1992) and Gradstein et al. (1992) with interpreted chronostratigraphy. The light grey/white intervals are nannofossil ooze (turbidites) and the dark grey horizons are siliceous ooze (pelagites). The green arrows are the palynology (paly) samples. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

bioturbated intervals near unit tops. In contrast to the calcareous nannofossil units, the siliceous units have much higher magnetic susceptibility and density. The sequence is interpreted as a sequence of pelagites (*in situ* radiolarian ooze) and hemipelagites (transported slope nannofossil ooze) of turbiditic origin near the calcium carbonate compensation depth (cf. Stow, 1985; Gradstein et al., 1992).

Radiolarian assemblages were used to date the upper part of ODP Site 765 (Kaminski et al., 1992; Gradstein et al., 1992) where cores 123-765 B-1H and 123-765 B-2H were assigned to the *Buccinosphaera invaginata/Collosphaera tuberosa* Zone (RN16/17 Zones of Sanfilippo and Nigrini, 1988), suggesting an age ≤ 590 kyrs at ~ 18.5 m (Fig. 2; Gradstein et al., 2012; Expedition 342 Scientists, 2012). Cores 123-765 B-3H to 123-765 B-8H are placed in the *Amphirhopalum ypsilon* Zone, indicating an age younger than 1.0 Ma. All the cores analysed lie in the Brunhes normal-polarity zone (Kaminski et al., 1992), however there is an interval of reversed-polarity from the lower part of Core 123-765 B-1H to the top of Core 123-765 B-2H (9–9.7 m, Fig. 2). This interval was suggested to represent a magnetic field excursion in the latest Pleistocene (Kaminski et al., 1992). Since the age at 18.5 m is ~ 590 kyrs it is possible that this reversed polarity interval correlates with a marine isotope stage 9 excursion event at 289 kyrs (Channell, 2017) if a linear sedimentation rate is interpreted for the section (Fig. 2).

The calcareous oozes (turbidites) are likely to have been rapidly deposited (geologically instantaneous). Thus the 8.8 m of these calcareous facies in the upper 12.25 m of section analysed were episodically accumulated in days (cf. Stow, 1985). However, these turbidites are interbedded with horizons of siliceous oozes representing slower “background” pelagic deposition that accumulated

at rates from 10^{-2} to 10^{-3} m/1000 years (the typical range for pelagites estimated by Stow, 1985).

4. Results

In general, palynomorphs were present in low concentrations with insufficient numbers for counts in many samples as palynomorph totals, including reworked taxa and fungal spores were low (1–184 total grains). Similar yields were recorded in the two samples previously studied in this section of the core (McMinn, 1992; McMinn and Martin 1992) that recorded low total counts (2 and 50 pollen, fern spore and dinoflagellates) with larger (20 cm³) samples. Nevertheless, thirty-eight spore and pollen and fern spore taxa are recorded in this study (Table 1) with the most common and abundant taxa including: Asteraceae, Amaranthaceae/Chenopodiaceae, *Eucalyptus* types, myrtaceous shrubs and Poaceae.

Twenty-one dinoflagellate taxa are present (Table 2), although some could not be identified beyond genus level. Most of the dinoflagellates recorded belong to the genera: *Impagidinium*, *Operculidinium*, *Protoperidinium* and *Spiniferites*. Acritarchs were divided morphologically into eleven distinct morphotypes and were either assigned to *Micrhystridium* spp. or occurred as simple round psilate forms that were classified based on size groupings in combination with aperture type. Fungal bodies were not identified as individual morphotypes. Reworked spores, pollen and dinoflagellates are also present. Most of the reworked fossil gymnosperms and spores had long time ranges but the presence of the dinoflagellate *Rigaudella aemula* suggests a middle to late Jurassic age for the reworked sediments based on the biostratigraphy of Helby et al. (1987). Although counts were low, concentration and qualitative data show

Table 1

Pollen and fern spore taxa recorded in ODP Site 765 and their probable source. Table derived from information in van der Kaars (1991, 2001), van der Kaars and De Decker (2002, 2003) and the Western Australian Herbarium website FloraBase (1998-).

	Western Australia origin	Western Australia (restricted to north) and Indonesia	Taxa Restricted to Indonesia
Trees and shrubs			
<i>Acacia</i>	+		
Annonaceae		+	
Araucariaceae			+
<i>Callitris</i>	+		
Casuarinaceae	+		
<i>Cupania</i>			+
<i>Dacrydium</i>			+
<i>Dacrycarpus</i>			+
Dipterocarpaceae			+
<i>Eucalyptus</i> types	+		
Myrtaceous shrubs	+		
Myrtaceae cf. <i>Syzigium</i>		+	
Moraceae		+	
Pittosporaceae?	+		
Podocarpaceae			+
Rubiaceae	+		
Santalaceae	+		
Sapindaceae	+		
Sapotaceae		+	
Herbaceous taxa (including woody herbaceous)			
Amaranthaceae/Chenopodiaceae	+		
Asteraceae (Tubuliflorae)	+		
Boraginaceae	+		
Brassicaceae	+		
Campanulaceae (cf. <i>Whalenbergia</i>)	+		
Cyperaceae	+		
Euphorbiaceae	+		
Fabaceae	+		
Gyrostemonaceae	+		
Haloragaceae	+		
Loranthaceae	+		
Poaceae	+		
Urticaceae	+		
<i>Verticordia</i>	+		
Ferns			
Aspleniaceae/Dryopteridaceae			+
Cyatheaaceae			+
<i>Dicksonia</i>			+
Polypodiaceae		+	
<i>Schizaea</i>	+		+

that the palynomorph assemblage varies through the section.

4.1. Pollen and fern spore distribution

This study confirms the observations of McMinn and Martin (1992) that the remoteness of the site >400 km from the Australian margin precludes the accumulation of significant pollen in palynomorphs assemblages. Nevertheless, sufficient diversity is present to describe and interpret the assemblages. The most common and abundant taxa are Myrtaceae (including trees and myrtaceous shrubs) and Poaceae (including grass pollen). Common taxa, which were not present consistently or abundantly, included: *Acacia*, Asteraceae Tubuliflorae and Amaranthaceae/Chenopodiaceae. Although these taxa are widespread across the entire region, their consistency and abundance in the samples in conjunction with the previous work on cores and core top samples offshore of north Western Australia (van der Kaars and De Decker 2002, 2003; van der Kaars et al., 2006) allows us to interpret them as being primarily sourced from the Australian mainland. All other taxa of a probable West Australian origin were recorded rarely or just once in the section examined. Fern spores are rarely recorded, occurring sporadically in the uppermost 4.6 m of the core.

The total concentration of *in situ* pollen (Fig. 3) is primarily controlled by the two most prominent taxa the Myrtaceae and

Poaceae. High Poaceae values occur in the surface sediments but also in most of the calcareous oozes deposited by turbidity currents. McMinn and Martin (1992) noted that relatively high levels of grass pollen types in their study of ODP Site 765 were surprising given their fragile nature, and suggested that differential destruction of the pollen types was not occurring in the record, therefore we can consider the grass values to be a true reflection of those being deposited at the site. The concentration of Myrtaceae pollen throughout the record is usually less than the grass. The two taxa in most instances co-vary, although there are instances e.g. at 3.6 m when grass occurs in the absence of Myrtaceous species.

Taxa not typically present in Western Australia and definitely interpreted to be sourced from Indonesia (based on comparisons with van der Kaars, 1991; 2001) are primarily gymnosperms including: Araucariaceae, *Dacrydium*, *Dacryocarpus* and *Podocarpus*. Indonesian-sourced fern spores (Aspleniaceae/Dryopteridaceae, Cyatheaaceae *Dicksonia*) and rare angiosperm pollen (Dipterocarpaceae) are also present. Indonesian sourced palynomorphs are sporadically present (Fig. 3) typically in nannofossil ooze turbiditic intervals.

4.2. Fungal spores and micro charcoal

Batten (1996) observed that fungal spores and micro charcoal

Table 2Dinoflagellate taxa in the top 12 m of ODP Site 765 and their environmental distribution derived from [Marret and Zonneveld \(2003\)](#).

Dinoflagellate taxa	Marine Environments	Temperature regime
<i>Achmosphaera</i> sp. McMinn (1992)	N/A	N/A
<i>Brigantedinium</i> spp.	Not restricted to any salinity	Not restricted to any temperature
<i>Impagidinium aculeatum</i> (Wall, 1967) Lentin and Williams 1981	A cosmopolitan species occupying a broad range of salinities	A dominant species in subtropical/tropical oceanic sites but is distributed within a broad range of temperatures
<i>Impagidinium paradoxum</i> (Wall, 1967) Stover and Evitt 1978	Fully marine environments.	Temperate to tropical
<i>Impagidinium patulum</i> (Wall, 1967) Stover and Evitt 1978	Fully marine environments.	Temperate to tropical with highest relative abundances in the tropics
<i>Impagidinium striatum</i> (Clarke and Verdier) Stover and Evitt 1978	Fully marine environments.	Temperate to tropical. In the Southern Hemisphere high abundances occur in tropical regions.
<i>Impagidinium</i> spp.		
<i>Lingulodinium machaerophorum</i> (Deflandre and Cookson) Wall, 1967	Coastal species that can tolerate a wide range of salinities	Temperate to tropical.
<i>Nematospaeropsis labyrinthus</i> (Ostenfeld) Reid, 1974	Cosmopolitan species able to tolerate a wide variety of environments. Present in high relative abundances both at coastal shelf sites and in the open ocean	Broad distribution from cold to tropical domains.
<i>Operculodinium centrocarpum</i> (Deflandre and Cookson, 1955) Wall 1967	Cosmopolitan species able to tolerate a wide variety of environments. High relative abundances in both deep-sea and coastal sites.	Broad distribution from cold to tropical domains.
<i>Operculodinium israelianum</i> (Rossignol, 1962) Wall 1967	Fully marine sites with highest relative abundances in associations of high salinity environments.	Temperate/subtropical to tropical species.
<i>Operculodinium janduchenei</i> Head, Norris and Mudie, 1989	Coastal to open oceanic, fully marine environments.	A temperate to tropical species
<i>Operculodinium</i> spp.		
<i>Pyxidinopsis reticulata</i> (McMinn and Sunn, 1994) Marret and de Vernal 1997	Cosmopolitan in fully marine environments	Wide temperature range.
<i>Pyxidinopsis</i> spp.		
<i>Spiniferites mirabilis</i> (Rossignol, 1964) Sarjeant 1970	Distributed within a broad range of salinity in fully marine environments.	Temperate to tropical species. distribution is limited by the subtropical fronts in both hemispheres.
<i>Spiniferites ramosus</i> (Ehrenberg, 1837) Mantell, 1854	Cosmopolitan species.	Broad range of temperatures.
<i>Spiniferites</i> spp.		
<i>Tuberculodinium vancampoae</i> (Rossignol, 1962) Wall, 1967	Coastal species that can be found in regions with enhanced or reduced SSS.	Subtropical/tropical
<i>Trinovantedinium applanatum</i> (Bradford) Bujak and Davies, 1983	High relative abundances have been found in sediments below river discharge waters, as well in highly stratified upper water masses. Can tolerate salinity fluctuations.	Northern Hemisphere to 45°S, broad range of temperatures and can tolerate temperature fluctuations.
<i>Votadinium calvum</i> Reid, 1977	N/A	N/A
Unknown Protoperidiniacean cysts		

were often reworked in marine environments as both are resistant to chemical and bacterial attack. The abundance of these groups is slightly reduced in the *in situ* pelagites (siliceous ooze) compared to the transported nannofossil ooze (turbidites) however overall, they show a relatively constant influx through time ([Fig. 3](#)).

4.3. Dinoflagellate and acritarch assemblages

The most common dinoflagellates at ODP Site 765 are similar to those described by [Hessler et al. \(2013\)](#) in marine seabed samples from the region. Species include: *Impagidinium aculeatum*, *Impagidinium patulum*, *Impagidinium striatum*, *Operculodinium centrocarpum*, *Spiniferites mirabilis*, *Spiniferites ramosus* and *Tuberculodinium vancampoae*. Total dinoflagellate concentrations show fluctuations that in most instances mirror the total pollen and spore concentration suggesting that they are controlled by suitable taphonomic and lithological processes for their presence in the core. An increase in concentrations of acritarch taxa in most instances corresponds to an increase in dinoflagellates suggesting that the marine deposition conditions equally suits all marine sourced palynomorphs at these times ([Fig. 3](#)).

5. Late Quaternary environments and climate

Marine sediment cores that have previously been used in Australia to reconstruct environments and climate from palynomorphs were located closer to shore and contained low energy deposited mud or carbonaceous mud, thus resulting in high palynomorph recovery (e.g. [Moss and Kershaw 2007](#); [van der Kaars and De Decker 2002](#)). In contrast, the sediment at ODP Site 765 are interbedded pelagites and turbiditic hemipelagites from the Argo Abyssal Plain at a water depth of over 5200 m. Despite the relative paucity of palynomorphs recovered from this deep-water site there are still sufficient palynoflora present to interpret "snap shots" of glacial/interglacial environmental/climate variability over the last ~300 kyrs.

5.1. Pollen and spore: a terrestrial record

The majority of the pollen and spore taxa at ODP Site 765 were interpreted by [McMinn and Martin \(1992\)](#) to have been initially deposited on the Northwest Australian shelf and subsequently transported by turbidity currents onto the abyssal plain. The present study confirms that this is an important taphonomic factor

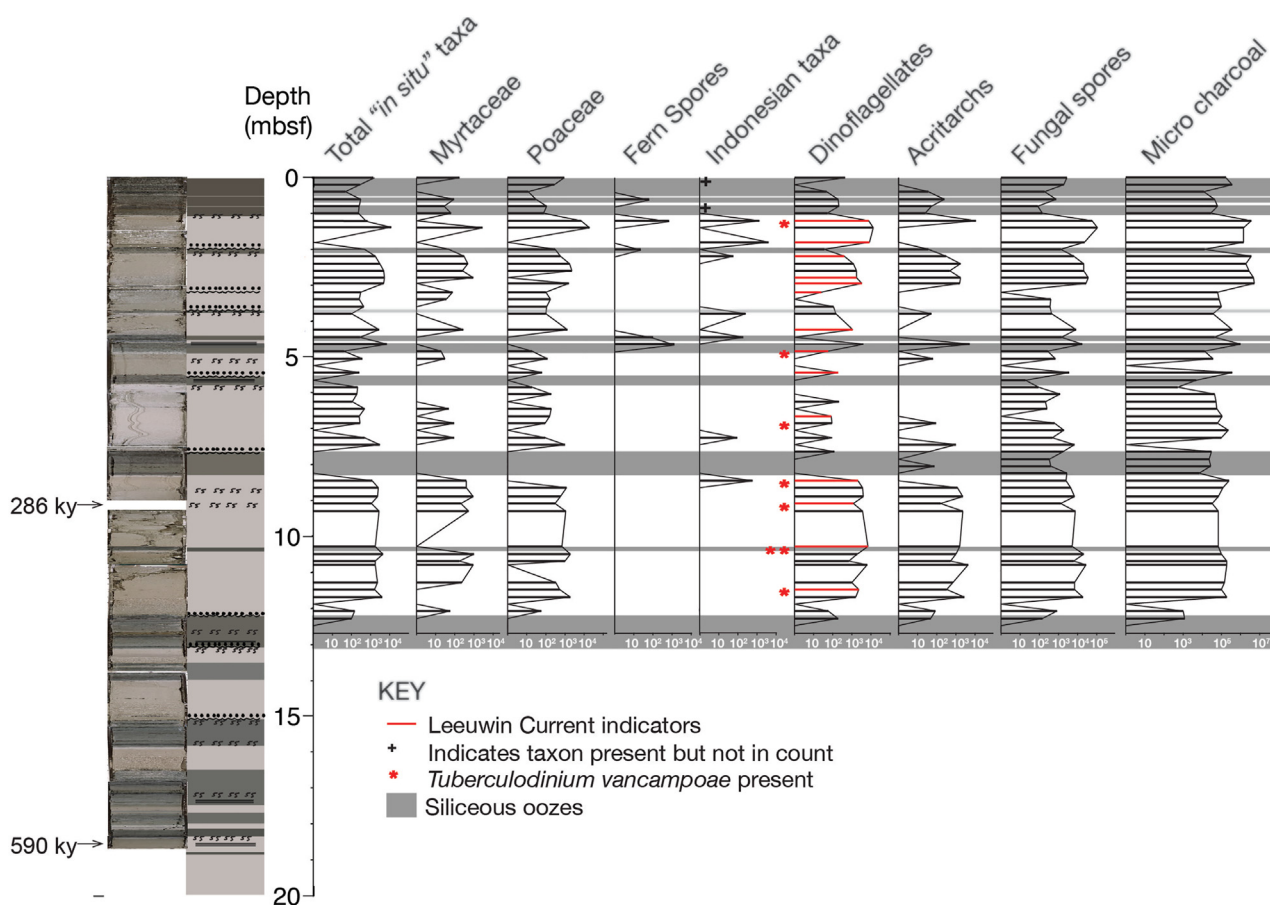


Fig. 3. The concentration in palynomorphs/cm³ of selected palynomorph groups at ODP Site 765. The concentration scale is logarithmic.

controlling the assemblage since *in situ* siliceous oozes yield a different assemblage to the rapidly deposited nannofossil ooze turbidite deposits. The siliceous oozes are interpreted to represent periods of slow sedimentation and yield low pollen and spore concentrations, as the pollen and spore source is far removed from the site of deposition with only wind and water currents transporting pollen and spore them this far out to sea. In some instances, they are essentially barren, this also might be due to oxidation on the seafloor. The nannofossil oozes contain relatively high amounts of grass pollen reflecting the “palaeo”vegetation mosaic of onshore Northwest Australia at these times. [van der Kaars and De Deckker \(2003\)](#) examined core top samples from offshore Western Australia and found that there was a strong relationship between onshore vegetation and climate zones in the adjacent offshore pollen assemblage. For example, north of 23°S the presence of higher grass values represents the monsoon vegetation with dominant summer rainfall. In contrast, outside monsoonal areas their core top pollen record was dominated by an assemblage of Asteraceae, Tubuliflorae and Chenopodiaceae/Amaranthaceae with relatively lower amounts of Poaceae. Interpretation of previous studies of a core taken offshore from Cape Range in Western Australia ([van der Kaars and De Decker, 2002](#)) also interpreted high grass values as representing the grass rich woodland vegetation of northwestern Australia and suggested a rainfall of 300–400 mm which primarily occurred in the summer ([van der Kaars et al., 2006](#)). Therefore, we interpret the intervals in ODP Site 765 yielding high grass signify the dominance of the summer monsoon.

The presence of Indonesian-sourced pollen and fern spore at ODP Site 765 is not unexpected as [van der Kaars and De Deckker](#)

(2003) noted an increase in Indonesian sourced fern spores in seabed samples off Western Australia, particularly north of 16°S. They suggested that these were transported southward via a strong Indonesian Throughflow-controlled Leeuwin Current. However, gymnosperms were the main Indonesian taxa recorded in this study. [Muller \(1959\)](#) and [Moss et al. \(2005\)](#) showed that gymnosperms are primarily transported into the marine realm by wind. [Muller \(1959\)](#) found that wind transport also makes a minor contribution to the angiosperm pollen assemblage in a marine environment. Therefore, it is also possible that long distance wind transport during the monsoon season may have carried Indonesian gymnosperm pollen to the site. Unfortunately the amount of definite Indonesian sourced pollen and fern spores is not at high enough levels or consistent enough to draw definite conclusions although at times in the record they do correspond, as would be expected, with the presence of Leeuwin Current indicative dinocysts.

5.2. Charcoal and fungal spores: continental fire history

The charcoal record in the top 12 m of ODP Site 765 suggests that fire was a constant presence in the adjacent landscape throughout the record. The correlation of high charcoal levels and a predominantly summer rainfall regime with the accompanying high biomass vegetation of open grassy Myrtaceae woodlands, had been noted by [van der Kaars and De Decker \(2002\)](#). This study confirms this correlation. In general, in ODP Site 765 the relative abundance of fungal spores follows the charcoal trend. The relationship between fire and fungal spores is not well known in northwest

Australia and further work on fungal morphotypes would be needed to draw conclusions about this record. However, this study does show that fire was a constant feature of the landscape in north Western Australia prior to human occupation of the region 65,000 years ago (Clarkson et al., 2017).

5.3. Dinoflagellates and acritarchs: the marine record

McMinn (1992) suggested that the dinoflagellates at ODP Site 765 were initially deposited on the shelf and subsequently transported by turbidity currents onto the abyssal plain. However, Hessler et al. (2013) examined modern marine surface samples in the region and showed that the majority of dinoflagellate taxa were *in situ* while benthic reworking mainly recycled coastal species. Therefore, the dinocyst assemblage reflect prevailing marine conditions at the site.

Marret and Zonneveld (2003) synthesised assemblage data from 835 marine seabed sediment samples to determine the relationship between dinocyst species distribution and the surface-water conditions (temperature, salinity, phosphate and nitrate concentrations). This comparative data set was further enhanced by Zonneveld et al. (2013) to develop a distribution atlas of modern dinoflagellate cysts and their relationship to environmental conditions. These authors characterised distinctive groups of species from cool, warm or extremely warm conditions, yet not necessarily restricted to each environment. The majority of the taxa at ODP Site 765 are ubiquitous (Table 2). However, warm species including: *Impagidinium aculeatum*, *Impagidinium patulum*, *Impagidinium striatum*, *Tuberculodinium vancampoae* are present with *Operculodinium israelianum*. *Tuberculodinium vancampoae* is restricted to SST's (sea surface temperatures) from 12 to 30 °C. All warm water dinoflagellates taxa occur in the nannofossil ooze intervals (turbidites). In addition, Hessler et al. (2013) found modern samples with the taxa *O. centrocarpum* and *S. mirabilis* typify Leeuwin Current conditions with elevated salinities and low nutrients. In this study the latter two taxa only occur in samples (Fig. 3) of nannofossil ooze/turbidites and are absent in the siliceous ooze deposits.

Some specific species e.g. *T. vancampoae* are likely to have been sourced from the coastal (estuaries, lagoons) realm according to Marret and Zonneveld (2003), and therefore indicate the transport of sediment downslope. Three other species (*Operculodinium centrocarpum*, *Operculodinium janduchenei*, *Spiniferites ramosus*) at ODP Site 765 are regarded by Zonneveld et al. (2013) to be characteristic of but not restricted to river plumes and estuaries. The presence of these species indicates that the coastal region source for some of the dinocysts in the nannofossil oozes were deposited via turbidity currents.

6. Discussion

6.1. Glacial/interglacial Leeuwin Current variability

The presence of common Leeuwin Current dinocyst indicators and Indonesian sourced palynomorphs in the transported nannofossil ooze (turbidites) and their absence in the *in situ* pelagic siliceous ooze, suggests slope instability during periods of stronger Leeuwin Current activity. Significantly, Spooner et al. (2011) interpreted a stronger Leeuwin Current during all interglacial phases over the last 550 kyrs (possibly during MIS (Marine Isotope Stage) 5 and MIS 7, MIS 11 and periodically during MIS 9) compared to the Holocene. Based on these data we suggest that the turbidites at ODP Site represent intermittent “snap shot” palynological records of interglacial conditions over the last 300 kyrs whereas the siliceous pelagites represent “background” low sedimentation likely deposited during the glacial periods (Figs. 3 and 4).

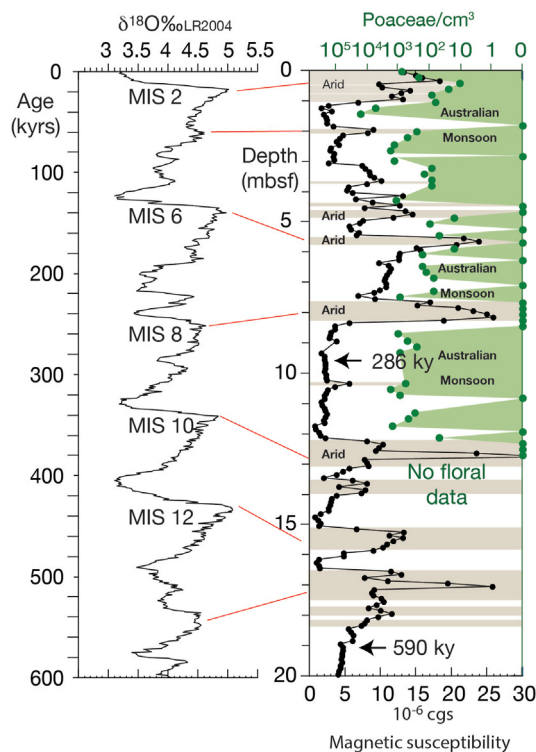


Fig. 4. A correlation between the Poaceae abundance and magnetic susceptibility at ODP Site 765 with the LR2004 stack (Lisiecki and Raymo, 2005). Note: in addition to the bio- and magnetostratigraphic datums that constrain the chronology of this section, the similarity between the magnetic susceptibility maxima/minima patterns and its correlation to the LR2004 stack allows the siliceous ooze horizons to be correlated with likely glacial maxima (especially intervals younger than 300 kyrs, the main focus of this paper).

6.2. The palaeomonsoon and aridity

Today summer monsoonal rainfall causes intermittent or infrequent flash flooding (Fig. 1d) of creeks and rivers that have an overall low discharge in the coastal region (Semieniuk 1992) southeast of ODP Site 765 off northwest Australia. These fluvial sediments are eventually deposited on the coastal plain in river delta systems, thus contributing to a plume of fluvial sand blanketing the shelf around the periphery of deltas (Fig. 1d; Semieniuk 1992). Stuut et al. (2014; 2019) suggest because of the present-day topography of the Northwest Australian region that active permanent major river systems (like the De Grey River) were present in the past and that the surface erosion of these rivers would have been immense, bringing extensive fluvial sediment supply to the ocean. Hesse et al. (2004) and Fitzsimmons et al. (2012; 2013) also showed that despite a long-term drying trend there was enhanced runoff in interglacial stages over the last 300ka at Lake Gregory (~20°S; Fig. 1b). Analyses of sedimentary cores in monsoonal northern Australia, suggest hot wet interglacials alternate with cooler dry glacials (Hesse et al., 2004; Gallagher et al., 2014; Gallagher and deMenocal, 2019). Further south off Cape Range (~22°S) analyses of a 1 million year continental slope (1093 m depth, GC) record (Stuut et al. 2014, 2019) shows pronounced and persistent aridity during glacial stages and more humid conditions during interglacials. Stuut et al. (2014; 2019) hypothesised that during interglacial stages increased seasonal rainfall led to an increased supply of terrigenous clay to the continental slope. During the glacials decreased rainfall led to the dominance of windblown sediment and foraminiferal and

nannofossil-rich carbonates. Between these two regions, a 2 million year shelfal record near Barrow Island also reveals strong interglacial/glacial variations in clay input over the last 2 million years, where green clayey sand predominated during interglacial wetter conditions (related to a stronger monsoon) and carbonates (with lesser terrestrially sourced siliciclastics) predominated during the dryer glacial phases as conditions became more arid (Gallagher et al., 2014; 2017; Keep et al., 2018; Ishiwa et al., 2019; Hallenberger et al., 2019).

These depositional models suggest that terrigenous sediment plumes are likely to carry evidence of the vegetation mosaic in the catchment area of each river in flooding events during enhanced monsoon conditions (especially during interglacial periods) onto large regions of the adjacent Northwest shelf and slope (cf. van der Kaars et al., 2006). These plumes transported terrestrial palynomorphs and coastal dinoflagellates to the shelf and slope and they were ultimately delivered intermittently to ODP Site 765 via turbidites during interglacials (Figs. 1d and 4). The siliceous ooze deposits in ODP Site 765 represent times of slow sedimentation with no input from the shelf. As such they yield an impoverished palynological assemblage, which are at times totally barren and it is likely that these deposits were formed during more arid glacial periods.

Based on the regional models above we use the alternations of Poaceae peaks with magnetic susceptibility maxima (low sediment input) to provide a possible correlation of the sediment at Ocean Drilling Program Site 765 (Fig. 4) to the LR2004 stack (Lisiecki and Raymo, 2005). This correlation is enhanced by the strong similarity between magnetic susceptibility pattern and glacial/interglacial variability of the LR2004 stack which is constrained by the chronological framework provided by biostratigraphic and magnetostratigraphic data. This stratigraphic approach is similar to that used to correlate physical core parameters with the LR2004 stack in shelfal sequences on the Northwest Shelf of Australia by Gallagher et al. (2014). Thus, the oldest sediment analysed for palynomorphs are ~300kyrs and that the slowly accumulating siliceous oozes likely preserve the majority of the glacial arid MIS events. Conversely, the faster accumulating calcareous oozes/turbidites capture intermittent “snap-shots” of the Australian monsoon during interglacial periods. The upper meter of siliceous oozes likely represents Last Glacial Maximum more arid conditions during MIS 2, however, the increase in Poaceae near the top suggests increased summer monsoonal activity associated with deglaciation during the Holocene. The lack of calcareous ooze on the seabed at present may be erosional.

7. Conclusions

Ocean drilling Program Site 765 was cored at ~16°S on the Argo Abyssal Plain in over 5.5 km water. It is directly influenced by Australian monsoon (during Austral summer), lies under the northwest Australian sourced dust belt (during the Austral winter) and is directly downstream of the Indonesian Throughflow. As such it is ideally situated to record signals of Quaternary climate/environmental variability. Despite being over 400 km from northwest Australia the presence of sufficient palynomorph concentrations of spores/pollen and microplankton allowed palynological analyses of the nannofossil ooze (turbidite) and siliceous ooze (pelagite) alternations in the upper 12 m of this site. This record reveals a highly variably assemblages related to changing ocean and climate conditions over the last ~300 kyrs. The nannofossil oozes (turbidites) were deposited primarily during periods with common grass pollen suggesting an onshore hinterland monsoonal vegetation similar to northwest Australia today. Indonesian sourced pollen and spore taxa in these assemblages were transported to the area via the

Indonesian Throughflow sourced Leeuwin Current or arrived aeri-ally via the palaeomonsoon. The dinoflagellates are primarily ubiquitous forms although there are warm water indicators and species that typify Leeuwin Current conditions with elevated salinities and low nutrients. Downslope transport brought coastal taxa such as *T. vancampoeae* to the site at these times. The siliceous ooze deposits formed during periods of low sedimentation rates in the absence of shelf input. They also yield rare or are barren of palynomorphs. It is likely that these deposits formed at times of low runoff from the coast during more arid glacial periods. The presence of common charcoal in all samples over the last 300 kyrs shows that fire was a constant feature of the landscape in north-west Australia prior to human occupation of the region 65,000 years ago.

Author statement

BW, Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Funding acquisition. SG, Investigation, Formal analysis, Writing – original draft, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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