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Key Points:
- Neighboring sites on the NW Australian shelf record different late Miocene sedimentation patterns due to diachronous basin subsidence
- A well-developed fluvial deposition system was established in NW Australia since at least 6 Ma
- Astronomically tuned age models confirm synchronicity of early Pliocene coccolithophore productivity and shifts in species composition

Supporting Information:
- Supporting Information S1
- Data Set S1
- Data Set S2
- Data Set S3
- Data Set S4
- Data Set S5
- Data Set S6
- Data Set S7

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Abstract
Pre-Quaternary paleoclimate studies in Australia mainly focus on terrestrial records from the southeastern part of the continent. IODP Expedition 356 drilled on the northwestern Australian shelf, yielding Miocene-Pliocene paleoclimate records in an area where climate archives are scarce. Postexpedition research revealed a dry-to-humid transition across the latest Miocene and early Pliocene (start of the “Humid Interval”). However, the complex tectonic history of the area makes these interpretations challenging. In this study, we investigate late Miocene to early Pliocene sediment cores from two sites that are only 100 km apart but situated in two adjacent basins (Northern Carnarvon and Roebuck Basins). Combining lithofacies study, time series analysis of potassium content (K wt%), and calcareous nannofossil abundance counts (N/g), this work disentangles the complex interplay between basin evolution and climate change between 6.1 and 4 Ma. Overall, the investigated proxies show high correlation between both sites, except during 6.1–5.7 Ma. During this interval, Site U1463 records a gradual increase in K wt%, correlated with basin deepening, whereas Site U1464 records an abrupt rise in K wt% at ~6 Ma. We explain this diachronicity by differential basin subsidence. The tectonic interplay with our paleorecords makes it difficult to pinpoint the exact onset of the “Humid Interval,” but we conclude that K wt% and coccolith abundances at Site U1464 indicate that a fluvial deposition system was already established since at least 6 Ma. This age is consistent with data supporting a southward movement of the Intertropical Convergence Zone rain belt at ~7 Ma.

1. Introduction
Northwestern Australia’s climate has strong seasonal contrasts, with a pronounced “wet season” during astral summer and a “dry season” in winter. Austral summer precipitation is due to the southward expansion of low-pressure monsoonal systems (de Deckker et al., 2014). Understanding the Neogene origins and long-term evolution of these climatic systems is a scientific challenge, because continental paleoclimate records are scarce and noncontinuous. It is therefore important to link the terrestrial processes with long-term marine paleoclimatic records on the continental shelves.

Previous work has revealed long-term and short-term fluctuations of arid and humid conditions during the Pleistocene and Pliocene, with a bias toward paleorecords from the southeastern part of the continent (Kershaw et al., 1994; MacPhail, 1997; Martin, 2006) and few records from the northwest (Stuut et al., 2014, 2019). More recently, the International Ocean Discovery Program (IODP) Expedition 356 drilled on the NW Australian shelf (NWS) shedding new light on Australia’s paleoclimate since the middle Miocene (Christensen et al., 2017; Gallagher et al., 2017; Groeneveld et al., 2017). However, concurrent processes that significantly affected the paleoceanographic archive on the shelf, such as intensified tectonic activity, add to the challenge of interpreting these records.

Late Miocene tectonic events include the reactivation of major faults in northern Australia (Cathro et al., 2003; Keep et al., 2007; Müller et al., 1998), driven by the northward movement of the continent. Fault reactivation accounted for subsidence in NW Australia under a contractional deformation regime and generation of submarine canyon systems that transported terrestrial sediments into the Expedition...
356 study area (Keep et al., 2007; Tagliaro et al., 2018; Woods, 1988, 1994). The major phase of tectonic activity occurred from 6–5 Ma and accounted for 300 m of subsidence, driven by a combination of long-term low frequency and more localized vertical motions (Gurnis et al., 2020).

Two initial studies were based on IODP Expedition 356 shipboard data and used downhole potassium (K wt%) wireline data as a proxy for terrigenous input and humid conditions, because K is primarily associated with weathered mineral phases (K-feldspars and clays) from the continent (Christensen et al., 2017; Groeneveld et al., 2017). Two nearby drilling sites (Sites U1463 and U1464, Figure 1), located in adjacent basins (Northern Carnarvon and Roebuck Basins, respectively), were investigated. The first study interpreted the middle to late Miocene K wt% record at Site U1464, suggesting persistent arid climate conditions during this time (Groeneveld et al., 2017), whereas the second study interpreted the younger K wt% record at Site U1463 and identified a latest Miocene to early Pliocene, rapid onset of a “Humid Interval” (5.5–3.3 Ma; Christensen et al., 2017).

The timing of the shift from arid to humid climate conditions correlates with intensified influence of the Indonesian Throughflow (ITF) and the Leeuwin Current (LC) driven by the expansion of the Western Pacific Warm Pool (WPWP) (Brierley et al., 2009; Zhang et al., 2014). The ITF is the surface current system that transports warm water from the WPWP into the Indian Ocean (Du & Qu, 2010; Gordon, 1997), and the LC is the major poleward current that is fueled by the ITF and transports warm waters southwards (Figure 1). Recent studies have confirmed the activity of the LC during the Pliocene and its relationship with ITF dynamics and sea surface temperature (SST) changes in the area (De Vleeschouwer et al., 2019). The position of the Intertropical Convergence Zone (ITCZ) during the onset of humid conditions would also have had an important influence on the amount of precipitation NW Australia was receiving (Auer et al., 2019; Bayon et al., 2017; De Vleeschouwer et al., 2018; Griffiths et al., 2009; Groeneveld et al., 2017).

However, an apparent ~0.5 Myr offset in the K wt% increase at these two neighboring IODP sites (5.5 Ma at U1463, Christensen et al., 2017, vs. ~6 Ma at U1464, Groeneveld et al., 2017) raises questions about the exact
timing of regional climate change or calls for alternative explanations. Here, we aim to explain this apparent
diachronous onset, by evaluating the refined age models and paleoceanographic records of both sites from
6.1 to 4 Ma. Our analysis includes the reassessment of the Natural Gamma Ray (NGR)-derived K wt% records
after they were astronomically tuned, the evaluation of the sedimentological and lithostratigraphic records,
and additional, detailed biostratigraphic and paleoceanographic data, including paleodepth estimates and
the abundance of small-celled, bloom-forming coccolithophores (Reticulofenestra and Gephyrocapsa spp.).
The latter phytoplankton species are associated with upwelling areas and high nutrient levels linked in turn
to terrigenous input (Ballegeer et al., 2012; Beltran et al., 2014; Chiyonobu et al., 2006; Kameo, 2002;
Takahashi & Okada, 2000).

2. Material and Methods

2.1. Lithostratigraphy and Potassium Content

IODP Expedition 356 Sites U1463 and U1464 are located only about 100 km from each other but are situated
in different basins on the NWS. Site U1463 is located in the eastern part of the Northern Carnarvon Basin
(18°58′S, 117°37′E, 145 m water depth), while Site U1464 was drilled at the western edge of the Roebuck
Basin (18°03.9′S, 118°37.8′E, 264 m water depth, Figure 1). The records at both sites are considered continu-
ous and benefit from correlation between different holes that created a compiled depth scale at each site
(CCSF-A, core composite depth below seafloor). All data presented herein are reported in meters CCSF-A
depth, following the shipboard splice (Gallagher et al., 2017). The lithostratigraphy for these sites was
divided into five lithostratigraphic units during shipboard investigations, originally reported on the CSF-A
(core depth below seafloor) depth scale (Gallagher et al., 2017). Our study interval includes three lithostratigraphic (sub)units at Site U1463 (290–460 m CCSF-A) and two at Site U1464 (150–330 m CCSF-A) (supporting information Table S1).

At Site U1463, Subunit IIIa, at 119.70–335.51 m CCSF-A (112.40–305.81 m CSF-A in U1463 Hole B), is
composed of homogeneous fine-grained mudstone and subordinate wackestone. Subunit IIIb, at
335.51–431.10 m CCSF-A (305.81–399.10 m CSF-A in U1463 Hole B), is composed of homogeneous
fine-grained mudstone and subordinate packstone and wackestone. Below, at 431.10–460.20 m CCSF-A
(399.10–428.20 m CSF-A in U1463 Hole B), Unit IV includes partially lithified to lithified, slightly dolo-
mitized grainstone (Figure 2 and Table S1). At Site U1464, Unit III is composed of unlithified mudstone and
ranges from 144.3–317.46 m CCSF-A (138.20–308.86 m CSF-A in U1464 Hole B). In the deeper part of
U1464 Hole B, Unit IV ranges from 317.46–324.95 m CCSF-A (308.86–316.95 m CSF-A) and includes
lithified dolomitic packstone, grainstone, and dolostone with gypsum and anhydrite nodules (Figure 2
and Table S1).

A simplified description of the abovementioned lithostratigraphic units, together with the shipboard micro-
paleontological data of the ratio of planktonic versus benthic foraminifers (expressed as % planktonic forami-

nifers [PF]; Gallagher et al., 2017), was used as a first-order indicator of relative changes in paleodepth at
each site (Figure 2).

The concentration of the element K, whether derived from wireline logging (e.g., Christensen et al., 2017),
NGR measurements on cores (De Vleeschouwer et al., 2017, 2019; this study), or XRF scans (Christensen
et al., 2017), has been used before as a proxy for river runoff and terrigenous input from the northwest
Australian continent (Christensen et al., 2017; De Vleeschouwer et al., 2018; Kuhnt et al., 2015). The K com-
ponent of the NGR-log is often used to infer the concentration of K-bearing aluminosilicates, mainly clays
and feldspars (Ehrenberg & Svarna, 2001). The most common clay minerals measured in the area’s rivers
include kaolinite and illite (Gingele et al., 2001). Kaolinite is primarily transported through wind erosion,
whereas illite, which is the main source of K in the clay fraction, has been linked to fluvial runoff
(Christensen et al., 2017; De Vleeschouwer et al., 2019; Mallinson et al., 2003). We therefore used the abun-
dance of K, as expressed by the weight fraction of K in a total gamma ray log (K wt%) as an indicator of clay
minerals transported into the basins through deltaic deposition. This interpretation is supported by the
strong covariation of downhole NGR measured Kw% with the clay mineral Illite at Site U1463
(Christensen et al., 2017) and XRF-derived K (counts) values from Site U1464 with other widely used proxies
for terrigenous input (Fe/Ca and Al/Ca, Figure S2).
NGR was measured on whole-round cores, and K wt% was determined from the characteristic gamma ray energies of isotopes in the 40 K radioactive decay series. A MATLAB algorithm, as presented by De Vleeschouwer et al. (2017), was used to integrate counts in element specific energy ranges of the NGR spectrum to quantify the sediment’s K content. At Site U1463, the NGR measurements come from Hole B and were taken at 20 cm intervals from the top of the hole down to Core 356-U1463B-31F (301.47 m CCSF-A; 275.27 m CSF-A). Below, measurements were taken at 10 cm intervals. At Site U1464, measurements were taken at 10 cm intervals in Holes U1464B, U1464C, and U1464D. Subsequently, a joint record of K versus depth CCSF-A was used for astronomical tuning.

2.2. Astronomical Tuning and Time Series Analysis
Sites U1463 and U1464 yielded a stratigraphic succession from the late Miocene to the early Pleistocene, with abundant and well-preserved calcareous nannofossils. Initial tie points were based on bioevents calibrated to the geological timescale of Gradstein et al. (2012, Table S2). The IODP Site U1463 age model used here is based on benthic foraminiferal δ¹³C and δ¹⁸O on Uvigerina spp. (Figure S3). Spectral analysis on the δ¹³C revealed the presence of the 405 kyr eccentricity record that could be correlated to the global carbon cycles (Cycles 5–12; Laskar et al., 2004). In a next step, the benthic δ¹⁸O was used for further tuning the global benthic δ¹⁸O stack LR04 (Lisiecki & Raymo, 2005). This new age model extends the range of previously published orbital age models for the site on both the older and younger end (Auer et al., 2019; De Vleeschouwer et al., 2018) and increases the temporal resolution and precision of the age model published by Christensen et al. (2017). Here, we present an astronomically tuned age model for Site U1464. In order to avoid any kind of circular reasoning, the K wt% record at Site U1464 underwent astronomical tuning independently from Site U1463 with the following approach. First, the NGR-derived K wt% record was assigned an initial age estimate based on four nannofossil bioevents (Table S4). These include the last occurrence (LO) of Discoaster tamalis at 2.8 Ma, the LO of Sphenolithus abies at 3.54 Ma, and the LO of Discoaster quinqueramus at 5.59 Ma (ages cf. Gradstein et al., 2012; Figure 3). An additional tie point was the marked decrease in small Reticulofenestra spp., a distinct biostratigraphic event observed at both sites (assigned an age of 4.51 Ma, based on the U1463 age model).
We then normalized and detrended the K wt% signal within three distinct intervals (piecewise normalization and detrending) in order to get a stationary signal (i.e., constant mean and variance throughout the time domain). Breaking points between different intervals were introduced at 3.6 and 5.56 Ma, to divide the U1464 record into three intervals, each with a virtually constant and linear trend in K wt% (noncalculative estimation). Following detrending and normalization, we subjected the K time series to evolutive harmonic analysis using the $3\times2\pi$ multitaper method (Thomson, 1982), as implemented in the R package astrochron (Meyers, 2014), to detect a possible imprint of astronomical climate forcing. Based on the observation of eccentricity periods in the K wt% power spectrum, the possibility to refine the age model through the application of cyclostratigraphy was explored. A band-pass filter was applied to extract variations in K wt% concentrations, related to the 405 and 100 kyr eccentricity cycles. The band-pass-filtered signal was then correlated to the La2011 eccentricity solution (Laskar et al., 2011). The signal was correlated with maxima and minima in the eccentricity 400 kyr solution, resulting in an age model of 12 depth-to-age tie points. To further fine tune the record, we iterated the same astrochronologic approach, using obliquity (40 kyr, using the La2004 obliquity solution, Figure 3; Laskar et al., 2004). The final U1464 tuning consists of 32 age-depth tie points, connecting the filtered waveforms from the K wt% signal to the corresponding cycles in orbital obliquity (Table S5).

The time step between age-depth tie points (median of 121 kyr) is thus significantly smaller than the biostratigraphy-based, Miocene age-depth model for U1464 presented in Groeneveld et al. (2017). This is relevant in the Miocene to Pliocene boundary interval, as our U1464 age model now provides the opportunity to scrutinize the ~0.5 Myr diachronicity in the timing of the late Miocene–early Pliocene large K wt% increase between U1463 and U1464.
2.3. Discrete Sampling: Benthic Foraminifer Stable Isotopes

As an additional control on correlating the records of Sites U1463 and U1464, a benthic stable oxygen and carbon isotope record was created for Site U1464 to allow direct comparison with the benthic isotope records of Site U1463 and the benthic δ¹⁸O LR04 stack (Figure S3; Lisiecki & Raymo, 2005). Stable oxygen isotopes were measured on Uvigerina sp. Up to 20 specimens were picked from the 250- to 400-μm-size fraction, which was extended to 150–250 μm when not enough specimens were present, per sample (n = 101, one sample per core) (from 356-U1464D-18H to 356-U1464D-34X). Stable isotope analyses were performed on a Finnigan MAT 251 gas isotope ratio mass spectrometer equipped with an automated carbonate preparation device at MARUM, University of Bremen. Isotopic results were calibrated relative to the Vienna Pee Dee belemnite (VPDB) using the NBS19 standard. The standard deviation of the house standard (Solnhofen limestone) was 0.03‰ for δ¹³C and 0.04‰ for δ¹⁸O during the measuring period.

2.4. Discrete Sampling: Calcareous Nannofossils

A total of 210 samples (105 samples from each site) was prepared for micropaleontological analysis. The sampling interval was ~1.5 m, covering at least one sample per core section. At Site U1463, the majority of samples were prepared from Hole C, except for five samples from Hole B. The deepest sample was from a core catcher (U1463B-48X-CC) reaching beyond the core recovery of Hole C. All samples at Site U1464 came from Hole B.

Sample preparation followed the “drop technique” (Bordiga et al., 2015). For each sample, 5 mg of dried bulk sediment was weighed and initially diluted with 20 ml of buffered water. After short sonification, the suspension was passed through a 63-μm-mesh sieve and further diluted to three different final concentrations (bulk-weight equivalent concentrations of ~0.125 mg/ml, 0.05 mg/L, and 0.03 mg/ml) deemed most suitable for counting coccoliths in the detrital carbonate-rich samples. Finally, 1.5 ml of well-mixed suspension was placed on a coverslip with a high-precision micropipette, and the sample was dried on a hot plate at 60°C. This technique results in an even distribution of particles on the coverslip. It also allows estimation of the concentration (“absolute abundance”) of calcareous nannofossils (coccoliths and nannoliths) per gram bulk sediment (in N/g) with a reproducibility of ±10–15% (Bordiga et al., 2015).

The micropaleontological data include the relative and absolute coccolith abundances of the dominant species. Calcareous nannofossils were examined under polarized light microscopy at 1,000X magnification. At least 300 specimens were counted in each slide and were identified at genus level, grouped by size classes. Herein, we only present the abundance data collected for small (<3 μm) Reticulofenestra and Gephyrocapsa species, ancestors of modern-day bloom-forming coccolithophore taxa such as Gephyrocapsa oceanica and Emiliania huxleyi. Whole assemblage data will be presented in detail elsewhere. Counts of biorstratigraphic marker species (e.g., Sphenolithus spp. and D. quinqueramus) refined the initial bioevent tie point used for the U1463 age model (Table S2). Finally, all nannofossil data were placed on the tuned age models for U1463 and U1464, as described in section 2.2.

3. Results

3.1. Tuned Records of Terrigenous Input and Basin Evolution

The age models for Site U1464 (this study) and Site U1463 (De Vleeschouwer et al., 2019; Figure S3) show a very good fit of the tuned U1463 and U1464 K wt% records (Figure 4a). Similarly, a good fit can be observed between the U1463 and U1464 benthic foraminiferal δ¹⁸O records, as well as the global benthic LR04 stack (Lisiecki & Raymo, 2005) (Figure 4b). The easily identifiable nannofossil Sphenolithus spp. abundance patterns also are highly similar between the sites (Figure 4c). Combined, these observations provide confidence that the recorded (bio)stratigraphic events are well dated and correlated at both sites. Importantly, our refinement of the initial, shipboard age models used in earlier studies (Christensen et al., 2017; Groeneveld et al., 2017) by astronomical tuning does not explain away the offsets in K wt% between 5.5 and 6.1 Ma (Figure 4a). The diachronicity in the K wt% increase between the two studied sites is thus a genuine characteristic of the NWS.

The K wt% records reveal a transition from low-to-high potassium values during the late Miocene (Figure 4a). However, the timing and the nature of this transition are, as initially suspected, markedly different between sites. At Site U1463, a gradual increase in K wt% is observed starting at ~6 Ma (~409 m CSF-A in
U1463 Hole B; 441 m CCSF A) and continues until further increasing at ~5.7 Ma (~387 m CSF A in U1463 Hole C; 421 m CCSF A) (Figure 5a). In contrast, at Site U1464, there is an abrupt increase in K wt% at ~6 Ma (~307 m CSF A in U1464 Hole C; 315 m CCSF A) (Figure 5a). Following this increase, the K wt% at both sites shows relative stability, with values that are overall higher at Site U1463 with some variation but without any significant increasing or decreasing trends.

Linear sedimentation rates (calculated between age model tie points) show similar values that range between 4 and 8 cm/kyr at both sites (Figure S4). Significantly higher sedimentation rates are only observed at Site U1464 in the interval from ~6.1 to 5.9 Ma and reach a peak value of 23 cm/kyr in the mudstone (Unit III).

The lithostratigraphic and paleodepth reconstructions (shipboard data; Gallagher et al., 2017) support a gradual deepening at Site U1463 (Figure 2). The deepening is recognized by a shift in lithofacies from a shallow...
Figure 5. Proxy records for terrigenous input, nannoplankton dynamics, and regional basin evolution from 6.1 to 4 Ma. (a) Potassium (K wt%) time series from Site U1463 (purple) and Site U1464 (black). (b) Relative abundances (%) of small (<3 μm) *Reticulofenestra* (red) and small *Gephyrocapsa* (blue). Light colors indicate Site U1463 and darker colors Site U1464. Error bars represent 95% confidence intervals. (c) Total nannofossil absolute abundances (N/g; all taxa). Light brown indicates Site U1463 and dark brown Site U1464. Open hexagons indicate core catcher samples, dashed lines = no data. Roman numbers indicate distinct stages in coccolith abundances. I_A = low total nannofossil and small *Reticulofenestra* abundances at Site U1463; I_B = rapid increase in total nannofossil and small *Reticulofenestra* abundances at Site U1463; II = rapid decline in total nannofossil and small *Reticulofenestra* abundances at both sites; III = increased *Gephyrocapsa* and moderate total nannofossil abundances at both sites. The same patterns persist also when considering nannofossil accumulation rates (Figure S5). (d) Simplified lithostratigraphy indicating the major changes in facies and thus depositional regime. Gray bar in upper right corner indicates interval of intensified tectonic subsidence in the Northern Carnarvon Basin (Gurnis et al., 2020).
marine carbonate (partially lithified to lithified, slightly dolomitized grainstone of Unit IV) to the finer, deeper facies (mudstone and subordinate packstone and wackestone of Unit IIIb, ~5.7 Ma) and a gradual increase in the proportion of PF (PF%), which intensifies after the change in lithology at ~5.7 Ma (Figures 2 and 5). At Site U1464, the deepening and the shift of the lithofacies happens much more abruptly at ~6 Ma with the transition from shallow marine carbonates and evaporates (Unit IV), to the deeper mudstone facies (Unit III 144.3–317.46 m CCF-A) paired with a sharp increase in PF% from <10% to >90% (Figures 2 and 5). In general, Site U1464 is interpreted as a deeper basin environment, with its estimated paleodepth always greater (upper bathyal) than that of U1463 (middle-outer shelf) during our study interval (Gallagher et al., 2017; Gurnis et al., 2020; Figure 2).

3.2. Coccolith Absolute and Relative Abundances

Coccolith abundances reveal highly similar patterns and trends at both sites. However, some differences in absolute and relative abundances exist. The highlighted stages (I, II, and III in Figure 5) indicate distinct changes in coccolith abundances and species distribution and help us constrain better the paleoclimatic and paleodepth (basin subsidence) inferences.

Small-sized (<3 μm) Reticulofenestra and Gephyrocapsa coccoliths are the most common during the late Miocene and Pliocene interval, and if grouped together, they constitute at all times between 27–85% and 34–87% of the total assemblage at Sites U1463 and U1464, respectively (Figure 5b). At Site U1464, total absolute coccolith abundances range from 2.78 × 10^8 to 2.43 × 10^10 N/g. The lowest coccolith abundance is observed in the deepest sample (U1463B-48X-CC, ~6 Ma) with an order of magnitude lower value (2.39 × 10^8 N/g). Following the period of low abundances (Stage IA), a rapid increase in absolute abundances is observed at ~5.7 Ma (~424 m CCF-A depth, Stage IB; Figure 5c), which is mainly due to an increase of small-sized Reticulofenestra species. The abundance of this group decreased again by nearly 1 order of magnitude from 1.03 × 10^10 N/g at ~4.56 Ma to 1.21 × 10^9 N/g at ~4.42 Ma (~371–357 m CCF-A depth, Stage II; Figure 5c). As small Reticulofenestra abundances decreased, the small Gephyrocapsa species started to increase (~4.42 Ma) and became dominant until the end of the studied interval, with maximum values of 4.49 × 10^9 N/g and 61% of the total assemblage (Stage III; Figures 5b and 5c).

At Site U1464, overall lower coccolith absolute abundances are observed ranging from 2.25 × 10^9 to 1.82 × 10^10 N/g. A rapid increase of coccolith abundances is observed here at ~6 Ma (~357 m CCF-A depth, Stage I; Figure 5c). Small (<3 μm) Reticulofenestra species dominate until their reduction by 1 order of magnitude, from 1.13 × 10^10 N/g at ~4.58 Ma to 1.67 × 10^9 N/g at ~4.41 Ma (~218–208 m CCF-A depth, Stage II; Figure 5c). Again, the decrease in Reticulofenestra is mirrored by an increase and subsequent dominance of small Gephyrocapsa species (~4.45 Ma) with 55% relative abundance and maximum concentrations of 3 × 10^9 N/g (Stage III; Figures 5b and 5c). Indeed, the character and rates of change in species composition between small Reticulofenestra and small Gephyrocapsa were comparable between both sites on timescales <100,000 years. These observations also confirm that the phytoplankton composition in the overlying surface waters, and thus the paleoecology, did not vary much on spatial scales of 100–1,000 km in this region.

Overall, total nannofossil fluxes (N/m²/kyr) follow the patterns observed in absolute abundances with synchronous timing and magnitude of the observed trends. Fluxes at Site U1463 are slightly higher after their initial increase from ~5.6–5.5 Ma and until their significant reduction at ~4.56 Ma. At Site U1464, nannofossil fluxes are ~5–6 times higher than at Site U1463 in the interval ~6–5.8 Ma (Figure S5).

4. Discussion

4.1. Regional Basin Evolution

Almost the entire NWS, from the Northern Carnarvon Basin to the Timor Sea, underwent accelerated subsidence during the Miocene and Pliocene. This started as early as 20 Ma in some areas and reached magnitudes of 500 m up to 1,000 km away from the Timor Trough (Müller et al., 1998). Localized activity and fault reactivation has been shown in the Roebuck Basin (up to 500 m subsidence) and the Northern Carnarvon Basin (Cathro et al., 2003; Keep et al., 2007; Müller et al., 1998), driven by the collision of the northward moving Australian plate with the Banda Arc during the late Miocene to early Pliocene (Tindale et al., 1998). The main stage of tectonic reactivation occurred from 6–5 Ma and accounted for 300 m of tectonic subsidence at Sites U1462 and U1463. Both sites are within the Northern Carnarvon Basin and despite their differences in...
sediment thickness revealed very similar kinematic tectonic models (Gurnis et al., 2020). The mechanism transporting sediments into our study area at that time has been described as an extended fluvial depositional system, controlled by the development of a large wave-dominated delta (Tagliaro et al., 2018). This system was shown to have initiated at ~5.59 Ma at Site U1463 based on an age model constructed with moderate resolution calcareous nannofossil data sampled at 10 m intervals. The start of extended siliciclastic deposition at Site U1463 was linked to the onset of humid conditions in NW Australia (Christensen et al., 2017), although the distributary deltas are believed to have started forming since the late Miocene (12–5.59 Ma, Tagliaro et al., 2018).

The paleodepth reconstructions and lithofacies interpretations support increased tectonic activity within both the Northern Carnarvon and Roebuck Basins during the late Miocene to early Pliocene (6–5.6 Ma). However, Site U1464 in the Roebuck Basin indicates a much more abrupt and significant deepening and change of the depositional regime already at ~6 Ma. Gurnis et al. (2020) discussed the possibility of a combined slower long wavelength (large-scale plate tectonics) and a localized high-frequency component (in-plane stresses) to account for the significant subsidence in the Northern Carnarvon Basin. It is possible that the high-frequency activity was more pronounced in the Roebuck Basin, accounting for a more rapid deepening.

The rapid shift from intertidal grainstones to mudstone facies with increased levels of siliciclastic material could even indicate the existence of a hiatus before ~6 Ma, likely caused by a stage of shelf exposure that occurred during the middle to late Miocene (Tagliaro et al., 2018). The high sedimentation rates inferred from our age model (Figure S4) for this time interval also support such increased tectonic activity in the area. The shift of the sedimentary facies and inferred deepening is more gradual (~6–5.6 Ma) at Site U1463, indicating different localized tectonic activity in the Northern Carnarvon Basin in comparison with the Roebuck Basin. The overall shallower paleodepth estimates (lower PF%) and the higher K wt% values may indicate that this site was located closer to the distributary delta than Site U1464. However, no significant differences in sedimentation rates are observed after both basins had reached a critical depth (5.7–4 Ma).

4.2. Coccolithophore Abundance, Preservation, and Productivity

Small, bloom-forming coccolithophore species are sensitive indicators of photic zone conditions, and their fossil record is generally used to interpret past surface eutrophication, upwelling conditions, and increased nutrient availability/terrestrial input (Beltran et al., 2014; Chiyonobu et al., 2006; Kameo, 2002; Takahashi & Okada, 2000). The relative abundances (%) of small *Reticulofenestra* spp. were high at both investigated sites since the late Miocene and appear independent from the sampled lithofacies (shallow marine carbonates vs. mudstone, Figure 5b). This suggests a relatively stable phytoplankton species composition and thus similar paleoecology within the late Miocene to early Pliocene surface waters overlying Sites U1463 and U1464. However, changes in absolute abundances (N/g) mainly indicate changes in regional basin evolution, as this measure is correlated to the presence of mudstone facies (Figures 5c and 5d). For example, the Core Catcher Sample 48X-CC at Site U1463 (~6 Ma) contains very low absolute coccolith abundances (N/g) within the partially lithified dolomitic grainstone (Unit IV) but similar proportions of small *Reticulofenestra* as in the overlying mudstone facies (Figure 5b). This observation can be attributed in part to generally worse preservation of the coccoliths in this lithofacies. The increase in absolute coccolith abundance and total nannofossil fluxes follows the subsidence of the basins and thus is also diachronous at the two studied sites (~5.7 Ma at Site U1463 and ~6 Ma at Site U1464; Figures 5 and S4). This happens due to better preservation of coccoliths in clay sediments (mudstone facies), which started dominating the lithostratigraphy following the differential subsidence in the two basins. Therefore, similar to the K wt% records, we can conclude that small, bloom-forming coccolithophores were already ecologically prominent in the area at 6 Ma.

After the initial increase, absolute abundances of small *Reticulofenestra* spp. remain high overall from 6–4.5 Ma. In contrast to the initial increase of coccolith abundances at both sites, the subsequent reduction in small *Reticulofenestra* abundances (at ~4.58 Ma) cannot be attributed to basin evolution (shallowing/uplift) since there is no large change in lithofacies, K wt% (clay content) or PF% at this time. The dominance interval, or acme, of small *Gephyrocapsa* spp. that follows (after ~4.5 Ma; Figure 5), continues into the late Pliocene and has previously been described as a “small *Gephyrocapsa* interval” in the midlatitudes of the Indian and Atlantic Oceans (Auer et al., 2019; Okada, 2000; Young, 1990).
This distinct change in species composition falls within a period of dominance of small reticulofenestrids (*Reticulofenestra minuta* <3 µm), which has been suggested to reflect eutrophic conditions and increased riverine input in the Indian Ocean since 8.8 Ma (Imai et al., 2015) and has even been linked to the onset of the Asian monsoon system at approximately 9–8 Ma (Sun & Wang, 2005; Zhisheng et al., 2001). Another scenario for the ecological prominence of this species during the late Miocene to early Pliocene includes increased continental erosion from 15 to 5 Ma (Johnson et al., 2009; Le Houedec et al., 2012). Finally, a late Miocene to early Pliocene period of increased productivity ("biogenic bloom"), possibly linked to increased nutrient availability due to chemical weathering of the Himalayas (Filippelli, 1997), has been shown to span from ~9 to 3.5 Ma in the Indian Ocean (Dickers & Owen, 1999). These previous observations are in part supported by our data. We observe higher total coccolith and small *Reticulofenestra* abundances co-occurring with increased terrigenous input (and humid conditions) in the late Miocene to early Pliocene. However, the decrease in absolute coccolith abundances occurred almost 1 Myr before the reduction in K wt% values and the inferred decrease in riverine runoff that occurred at around 3.3 Ma at Site U1463 (Christensen et al., 2017). Hence, there might be another environmental trigger for this change in coccolith abundances and the subsequent species composition changes. Dickens and Owen (1999) showed that the major stage of the biogenic bloom occurred ~6–5 Ma in the Indian Ocean. This means that the reduction in small *Reticulofenestra* abundances in the Northern Carnarvon and Roebuck Basins could be part of a larger-scale event associated with the end of the Pliocene biogenic bloom in the Indian Ocean. Another, more regional trigger that could influence nanoplankton species distribution is the significant increase in SSTs observed ~4.6 Ma at nearby ODP Site 763A (Karas et al., 2011). Gafar and Schulz (2018) demonstrated that *E. huxleyi*, arguably the modern analog of small *Reticulofenestra*, has a wider temperature tolerance and grows faster than *G. oceanica* in cooler temperatures. However, *G. oceanica* shows preferential optimal nutrient assimilation in higher temperatures (above 25°C). Similarly, small *Gephyrocapsa* spp. are commonly associated with warmer, stratified waters in tropical continental margins (Auer et al., 2019; Boeckel & Baumann, 2008; Bollmann, 1997; Okada & Honjo, 1973; Takahashi & Okada, 2000), whereas the fossil species *R. minuta* (small *Reticulofenestra*) has been interpreted to indicate waters rich in terrigenous input and increased nutrient supply (Auer et al., 2015; Lohmann & Carlson, 1981; Wade & Bown, 2006).

Despite the ecological affinities related to the dominance of small *Gephyrocapsa*, the two small coccolith-bearing species generally indicate a mesotrophic-eutrophic environment (Athanasiou et al., 2017; Colmenero-Hidalgo et al., 2002; Gartner, 1988; Takahashi & Okada, 2000) where opportunistic, fast-growing, and bloom-forming species are dominant at all times. This would support that terrigenous supply to the NWS was likely a persistent feature during the late Miocene to early Pliocene.

### 4.3. Earlier River Runoff and Humid Conditions in NW Australia

By extending the paleorecords at Site U1463 back to ~6.1 Ma and comparing these to the same time interval at nearby Site U1464, we confirm a diachronous deepening of the studied basins during the late Miocene to early Pliocene. This subsidence generated the accommodation space needed to record terrestrial clay influx (Tagliaro et al., 2018), thus preserving the K wt% record and small-sized coccolith abundances.

Although both these proxies point toward an established fluvial deposition system in the area by the late Miocene, it becomes clear that their values depend strongly on basin depth and on the sites’ positions within the deltaic system. Christensen et al. (2017) first observed a steep increase in K wt% at Site U1463 at ~5.5 Ma and described this change as the onset of humid conditions in northwestern Australia. Our analysis of the extended Site U1463 record highlights a rather progressive increase in K wt% that started already around ~6 Ma and followed the tectonic subsidence of the Northern Carnarvon Basin between 6 and 5 Ma (Gurnis et al., 2020), corroborated by changes in paleodepth estimates and lithostratigraphy. The deeper setting of the Roebuck Basin, as depicted at Site U1464, recorded higher mud and therefore higher K wt% concentrations at ~6 Ma, suggesting that a fluvial network transporting siliciclastic material was already in place in the area at that time.

We can exclude that the observed diachronicities in K wt% and coccolith abundances in two neighboring sites are due to age model discrepancies between the two sites (Figure 4). Instead, the differential patterns are most likely controlled by the tectonic evolution of the sedimentary basins, rather than a true diachronicity in the prevailing climatic conditions over NW Australia. The location of Site U1464 close to one of
Roebuck Basin’s major tectonic structures, the Mermaid Fault Zone, could be the reason for more abrupt tectonic subsidence at ~6 Ma. This fault zone was reactivated during the late Miocene, and although it is mainly a strike slip zone, it generated localized subsidence and triggered reef formation (Power, 2008; Ryan et al., 2009). At the same time, we can confidently exclude the possibility that paleoclimatic mechanisms were expressed almost 400 kyr earlier at Site U1464, a highly unrealistic scenario for sites that are only 100 km apart and that are both affected by large-scale processes.

After the initial increase, K wt% values remained similar in the area for several hundreds to thousands of years, with distinctive cyclicity but no significant trend, until they finally decreased at ~3.3 Ma (Christensen et al., 2017). This, together with the constant deeper depositional conditions since ~6 Ma at Site U1464 and the dominance of small, opportunistic coccolithophores, supports that precipitation and terrigenous input through a well-established river discharge system were enhanced prior to that time and persisted over a long period. These conditions would call for a more humid late Miocene to early Pliocene compared to the period after 3.3 Ma. Indeed, previous studies have indicated a poleward expansion of the WPWP to the South China Sea and the Indian Ocean since at least 6 Ma, which would have impacted low-pressure monsoonal systems over Australia (Brierley et al., 2009; Karas et al., 2011; Zhang et al., 2014). A southward shift of the ITCZ that resulted from the late Miocene Northern Hemisphere climate cooling and the intensification of the Southeast Asian winter monsoon could have been a potential driver for the increase in precipitation (Christensen et al., 2017; Herbert et al., 2016; Holbourn et al., 2018). A climate model by Broccoli et al. (2006) demonstrated how the Northern Hemisphere cooling is expected to move the ITCZ southwards and increase precipitation in the Southern Hemisphere in latitudes from the equator and up to 20°S. Holocene studies support this mechanism based on the Northern Hemisphere cooling, southward expansion of the ITCZ, and increased precipitation over northern Australia (Bayon et al., 2017; Griffiths et al., 2009). Finally, pollen data from Site 763A also support increased precipitation in NW Australia close to the late Miocene/early Pliocene transition (Andrae et al., 2018). However, this study proposes a mechanism where the southward shift of the ITCZ and the increase in seasonal precipitation occurred after 3.5 Ma, whereas a more constant precipitation pattern was present until then.

Our data support enhanced moisture supply and river runoff during the early Pliocene, but the question remains what the preceding conditions were and if an abrupt transition from aridity to humidity occurred somewhere during the latest Miocene. Groeneveld et al. (2017) described evidence for aridity at Site U1464 until at least 12 Ma, based on the presence of sabkha-like sediments that also confirm the shallow paleodepth of the site until the middle Miocene. Tagliaro et al. (2018) concluded that extended siliciclastic deposition started at 5.59 Ma in the Northern Carnarvon Basin, based on the U1463 lithostratigraphic record. However, they also highlighted that the interval between 12 and 5.59 Ma was a transitional period, in which a series of sandbars with associated small wave-dominated deltas evolved into a large deltaic system in response to an increasingly humid climate. Our interpretation of this complex system is that there was indeed a transition from arid to more humid conditions during the late Miocene. This transition was not abrupt, and it followed the increase in precipitation and the progressive buildup of a deltaic system. However, localized tectonic activity and the relative position of the studied sites within this highly dynamic system accounted for the significant differences we observe in lithofacies. Additional paleoclimatic records at locations on the NWS where depositional basin settings and distance to the paleoshoreline were more stable through the late Miocene to early Pliocene could further resolve the abovementioned climatic transition.

5. Conclusions

Northwestern Australia went through major tectonic subsidence between 6 and 5 Ma (Gurnis et al., 2020) that affected the adjacent Roebuck and Northern Carnarvon Basins differentially. Late Miocene deformation of the northern boundary of the Australian plate impacted the potential of those basins to record paleoclimatic conditions on the NWS. The diachronous increase of K wt% in our study sites is therefore a response to basin development and subsidence, rather than climatically driven or due to (initial) age model discrepancies. The limited accommodation space in the Northern Carnarvon Basin at ~6 Ma affected the sedimentary record and therefore did not record the exact onset of humid conditions and increased terrestrial inputs. The basins only documented river runoff and terrestrial input when they were properly placed inside the...
evolving deltaic system and deep enough to record changes in the potassium-based (K wt%) proxy for humidity and continental runoff. The lithostratigraphy, paleodepth estimates, and abundance of small coccolithophore species also support this conclusion. Therefore, based on these drill sites, we cannot establish the exact time when the “Humid Interval” over NW Australia started, but we can be confident that a deltaic system and siliciclastic deposition were already established in the area since at least 6 Ma. These observations suggest an earlier, progressive establishment of humid conditions than the Southern Hemisphere compilation studies of pollen and vegetation, which place the reversal of Miocene aridification close to the Miocene to Pliocene boundary (Kennett & Vella, 1975; Sniderman et al., 2016), but they are consistent with other marine proxy data and models supporting a southward movement of the ITCHZ rain belt at ~7 Ma (Holbourn et al., 2018).

Data Availability Statement

Data sets for this research have been uploaded to Pangaea data repository and can be found online (DOI: https://doi.pangaea.de/10.1594/PANGAEA.920082; https://doi.org/10.1594/PANGAEA.919913). Data are restricted and will become publicly available upon publication of the manuscripts. Data for this manuscript have also been uploaded as the supporting information.

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