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Short communication

Late Quaternary inundation and desiccation of Megalake Chad traced in dust records from the Equatorial Atlantic Ocean

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ABSTRACT

Modern Lake Chad has shrunk in area by around 90 % since the 1960s under the twin pressures of climate change and increasing water demand. During the early to mid Holocene, the Chad basin featured a megalake with an area approximately 100 times larger than its modern remnant. In the mid/late Holocene (approximately 5000 years ago), this megalake dried out leaving behind vast deposits of readily deflated fine-grained sediments that are suggested to contribute ~25 % of the annual total global atmospheric mineral dust load. Erosion has obliterated much of the evidence of earlier North African humid periods within the Lake Chad basin, limiting our understanding of the relationship between global/regional climatology, local hydrology and dust export. Here, we present new records of thorium-normalized flux estimates of mineral dust and its radiogenic isotope composition deposited at Ocean Drilling Program Site 662, situated downwind of Megalake Chad underneath the North African winter dust plume, in the equatorial Atlantic Ocean. Our records show that sediments of the Megalake Chad basin have a distinct neodymium isotopic signature that can be traced thousands of kilometers downwind from their source when the megalake basin was dry and dust-active, whereas the fingerprint of its input was strongly suppressed at times of high lake levels. Our results show that marine sedimentary archives can preserve uninterrupted proxy records of climate-driven hydrological change on the continents, in this case, a bellwether region of Africa that features the world's most active dust source, the Bodélé Depression.

1. Introduction

Mineral dust is an active agent in the Earth system: influencing regional radiation budgets, providing nutrients to terrestrial and marine ecosystems and impacting hazardously on human health and socio-economic infrastructure (e.g. Goudie and Middleton, 2006; Kok et al., 2023; Shao et al., 2011). Approximately half of the world's dust is produced in North Africa and half of North African dust is suggested to originate from the Bodélé Depression, making it the world's single largest source of dust (by flux) to the atmosphere (Ginoux et al., 2012; Prospero et al., 2002). Situated at the northern end of the endorheic Chad basin and lying about 155 m above sea level, the exceptional dustiness of the Bodélé

Depression is controlled by two phenomena. First, the availability of thick, readily deflated deposits of lacustrine sediments left behind at the end of the most recent North African humid period (AHP) ~5 kyr ago by the desiccation of Megalake Chad, an early/mid-Holocene waterbody many times the size of the modern Lake Chad (e.g. Armitage et al., 2015; Bristow et al., 2009). Second, strong winds resulting from funnelling of the northeast trades between the Tibesti and Ennedi mountains, export dust dominantly in a southwesterly direction towards the Atlantic Ocean (Meng et al., 2017; Schepanski et al., 2009; Washington et al., 2006a, 2006b).

Spanning the boundary between the Sahara and Sahel, the Chad basin is suggested to behave as a climatological tipping point, highly

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sensitive to shifts in seasonal rainfall patterns linked to the West African monsoon (Franzke et al., 2022; Lenton et al., 2008; Washington et al., 2009). Furthermore, because the Lake Chad basin is endorheic (i.e. it has no outlet to the ocean), changes in the regional hydrological cycle drive dramatic fluctuations in the extent of Lake Chad. Ancient lake shorelines, palaeodeltas and fine-grained lacustrine sediments and diatomites reveal that much of the basin was covered by a megalake as recently as ~5 kyr ago (Drake and Bristow, 2006; Schuster et al., 2005; Swezey, 2001; Tilho, 1925). Thus, because of its location in the heart of North Africa and isolation from the ocean, the Chad basin has the potential to provide important clues on both the mechanistic forcing of past changes in rainfall climate and on the inability of most global climate models to simulate them (Brierley et al., 2020; Hopcroft and Valdes, 2021). However, the pre-Holocene climate record on land is challenging to read because of extensive erosion and dating uncertainties.

Marine sediments can provide a continuous archive of exported continental dust, allowing reconstructions of temporal variability in North African continental climate over timescales from centuries to millions of years (e.g. Adkins et al., 2006; Collins et al., 2013; Crocker et al., 2022; deMenocal, 1995; Kinsley et al., 2022; McGee et al., 2013; Mulitza et al., 2010; Palchan and Torfstein, 2019; Skonieczny et al., 2013; Tiedemann et al., 1994; Tjallingii et al., 2008). However, most published North African dust records come from core sites north of ca. 10°N, preserving records of dust dominantly sourced from northwestern Africa, whereas dust from the Bodélé Depression and the wider Lake Chad basin is mainly transported further south by the northeast trade winds, particularly during winter (Meng et al., 2017; Schepanski et al., 2009). Here, we present new records of dust flux and provenance from North Africa to the equatorial Atlantic Ocean and compare them to land-based records to develop a continuous record of Megalake Chad inundation/desiccation over the past 30 kyr.

2. Materials and methods

2.1. Study site

Ocean Drilling Program (ODP) Site 662 (1.390°S, 11.739°W, 3814 m water depth) is located on the upper eastern flank of the Mid-Atlantic Ridge, to the south of the Romanche Fracture Zone (Fig. 1). ODP Site 662 is located >700 km from the continental slope edge and is not proximal to the mouth of any major river systems. Its position on the eastern flank of the mid-Atlantic ridge protects it from riverine inputs from South America, with little influence of redistribution by bottom currents on reconstructed terrigenous fluxes (Rowland et al., 2021). Thus, terrigenous supply to ODP Site 662 is dominated by windblown dust.

ODP Site 662 sits underneath the southern route of North African dust export (Meng et al., 2017; Pokras, 1991; Schepanski et al., 2009), where strong northeasterly trade winds (the Harmattan) transport large volumes of dust from the interior of North Africa out into the Gulf of Guinea and equatorial Atlantic, particularly during boreal winter (Fig. 1, Crocker et al., 2025; Dobson and Fothergill, 1981; McTainsh, 1980; Ruddiman and Janecek, 1989; Yu et al., 2019). When the Harmattan winds reach the intertropical convergence zone (ITCZ) which occupies a southerly position during winter, dust-laden air is lofted higher into the atmosphere and can be transported westwards as far as South America (Abouchami et al., 2013; Ben-Ami et al., 2010; Prospero et al., 1981), while some of the dust load is lost from the atmosphere via wet deposition (e.g. Rowland et al., 2021; van der Does et al., 2020).

2.2. Analytical techniques

The radiogenic isotopic signature of terrigenous sediments can be an effective tracer of sediment provenance (e.g. Blanchet, 2019; Grousset and Biscaye, 2005; Scheuvs et al., 2013). Here, we present new analyses of the neodymium isotopic values (ϵ_{Nd}) of isolated lithogenic

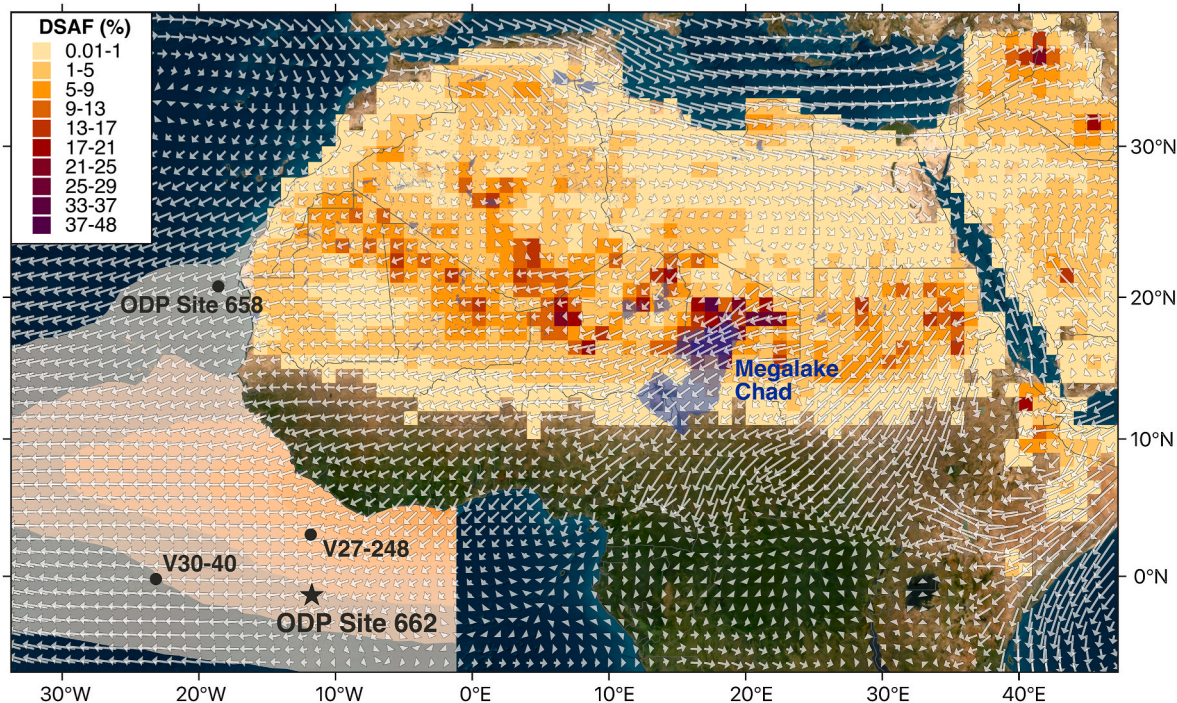


Fig. 1. Map of North African dust sources and transport pathways. Annual dust source activation frequencies (DSAF %, squares, Kunkelova et al., 2022; Kunkelova et al., 2024; Schepanski et al., 2012). Arrows indicate average 850 hPa January winds from 2010 to 2019 from ERA5 reanalysis (Hersbach et al., 2023). Winter dust over the Atlantic Ocean (pale orange) mapped by MODIS aerosol optical depth data, redrawn from Meng et al. (2017). Satellite basemap from Esri world imagery (Esri, 2023), with maximum extent of water bodies during African humid periods shown in dark blue (Manning et al., 2023). Location of ODP Site 662 marked with black star with other sites discussed shown by black dots.

fraction of sediments from ODP Site 662 (following the method of Jewell et al. (2022) to remove carbonate, organic matter, authigenic coatings, biogenic silica and marine barite). We compare these data to newly-updated dust source activation frequency (DSAF)-weighted radiogenic isotopic signatures of updated preferential dust source areas (PSAs) to reconstruct the importance of the Lake Chad basin as a dust source. We also present new thorium-normalized estimates (e.g. Adkins et al., 2006; Bacon, 1984) of dust fluxes to ODP Site 662. For full method details, see Supplementary Information (which also includes stratigraphy and supporting X-ray fluorescence and benthic oxygen isotope

datasets).

3. Results and discussion

3.1. Preferential dust source areas of North Africa and their geochemical fingerprints

To provide a framework to study changes in windblown dust supply to the equatorial Atlantic Ocean, we first define new preferential dust source areas (PSAs) for North Africa. Our new PSAs (Fig. 2) and their

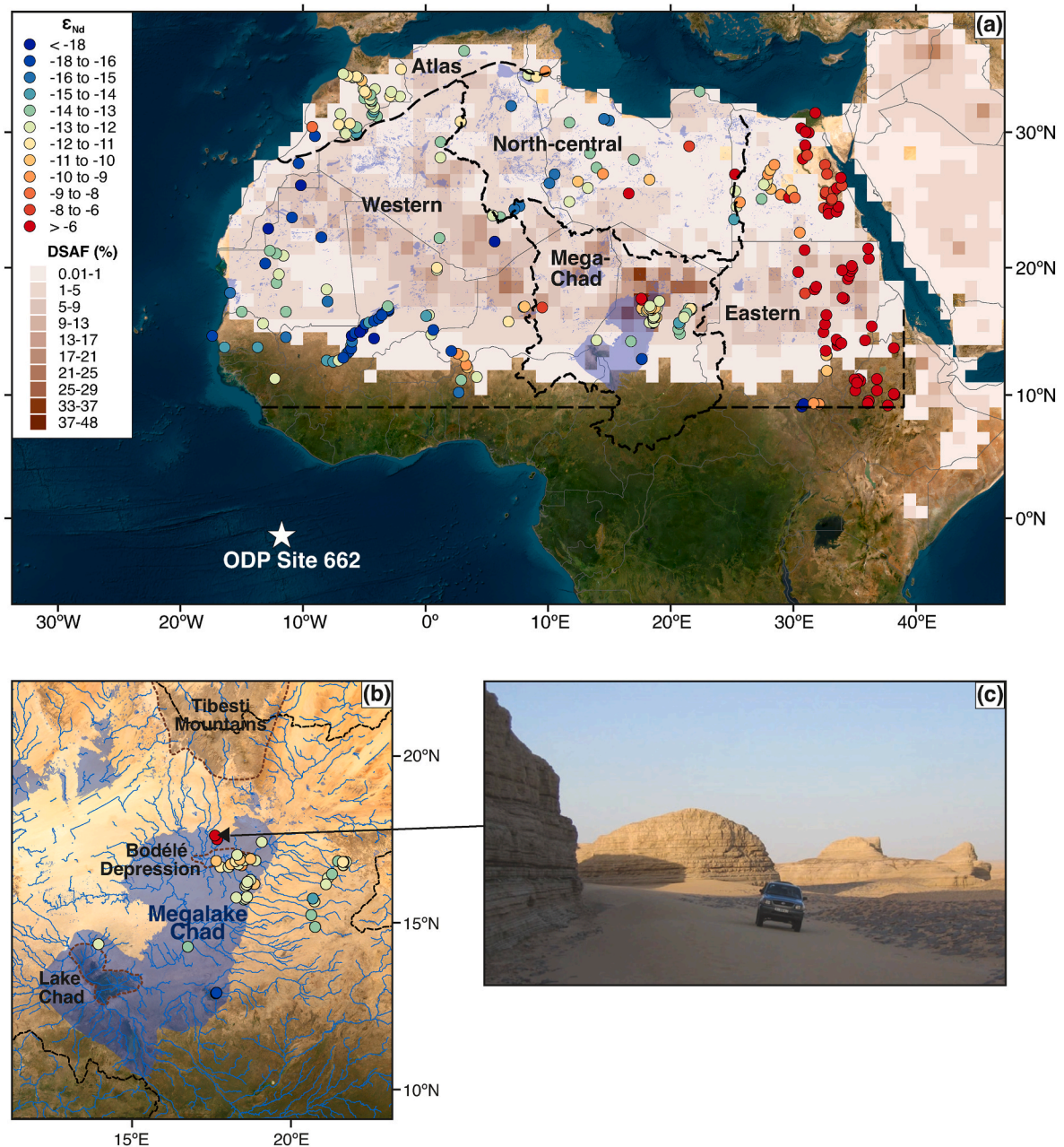


Fig. 2. Dust sources in North Africa and the Lake Chad basin. a) Map of annual dust source activation frequencies (DSAF %, brown squares, Kunkelova et al., 2022; Kunkelova et al., 2024; Schepanski et al., 2012), with coloured circles indicating neodymium isotopic compositions (ϵ_{Nd}) of dust-producing substrates (this study, Guinoiseau et al., 2022; Jewell et al., 2021 and references therein). Black dashed lines distinguish the five main preferential dust source areas (PSAs) shown in Table 1. Satellite basemap from Esri world imagery (Esri, 2023), with maximum extent of water bodies during African humid periods shown in dark blue (Manning et al., 2023). Location of ODP Site 662 marked with white star. b) Maximum extent of surface water bodies and palaeodrainage during past humid periods (blue) around Megalake Chad, with ϵ_{Nd} of dust-producing substrates superimposed using same colour scheme as panel (a). Key features marked with dashed brown lines. c) Photograph of ~10m high yardangs produced by wind erosion of Holocene sediments of the Angamma delta at the northern limit of Lake Megalake Chad, from Bristow (2023).

geochemical fingerprints (Table 1) were defined by updating the radiogenic isotope data compilation of Jewell et al. (2021) to include new and recently published data sets and by applying dust source activation frequency (DSAF) weightings (see Supplementary Information). Here, we primarily use neodymium isotope ratios (which depend strongly on bedrock geology (e.g. Bayon et al., 2015; Blanchet, 2019; Robinson et al., 2021; Scheuvs et al., 2013)) to characterise five North African PSAs. The MegaChad PSA is enclosed by the Chad basin catchment boundary and is isotopically heterogeneous, meriting further discussion.

We estimate that dust produced within the MegaChad PSA has an average ϵ_{Nd} value of -9.7 ± 3.9 (1 S.D.) (Table 1, Supplementary Fig. 1). The Megalake Chad basin shows a large range of isotopic signatures because the catchment is bounded to the north by, atypically for much of North Africa, young volcanic massifs such as the Tibesti (Suayah et al., 2006). Thus, sediments of Megalake Chad, and the Bodélé Depression in particular, show the influence of mixing from several isotopically distinct sediment sources (Jewell et al., 2021). Today, Lake Chad is largely fed from the southeast by the Chari River system. When past water levels were high, the Bahr el Ghazal palaeoriver system connected Lake Chad to the Bodélé Depression carrying sediments with $\epsilon_{Nd} \approx -12$ northwards (Bristow, 2023; Jewell et al., 2021). In addition, multiple small palaeorivers flowed westwards from the Ennedi mountains, carrying relatively unradiogenic material ($\epsilon_{Nd} \approx -12$ to -14) into the megalake (Drake et al., 2011; Jewell et al., 2021, Fig. 2b). Immediately north of the Bodélé Depression, rivers that drained the young volcanics of the Tibesti mountains during past humid intervals delivered sediments with very radiogenic ϵ_{Nd} signatures (ca. -3.8) to the Angamma Delta and then onwards into the Bodélé (Jewell et al., 2021). It has been suggested that these very radiogenic values are anomalous and unrepresentative of dust produced in the region (Guinoiseau et al., 2022). However, that argument is untenable because (i) annual DSAF values in this locality are the highest currently reported anywhere in North Africa (and therefore the world) (Schepanski et al., 2012, Fig. 2a) and (ii) giant yardang structures (up to 10m high) provide evidence of extensive wind-driven erosion of huge volumes of sediment from these deposits since the end of the AHP (Bristow, 2023; Bristow et al., 2009, Fig. 2c). We therefore include all ϵ_{Nd} values in our estimation of the signature of dust exported from the Megalake Chad basin. Our estimate for the MegaChad PSA is in good agreement with the most radiogenic ϵ_{Nd} values recorded in African dust reaching the Amazon (-9.9 , Barkley et al., 2022) and a dust trap sample taken within the Bodélé Depression (-10.7 , Guinoiseau et al., 2022).

3.2. Windblown dust supplied to the equatorial Atlantic Ocean provides a proxy record of inundation/desiccation of Megalake Chad

ODP Site 662 sits directly downwind from the remnants of Megalake Chad (including the Bodélé Depression, the most dust-active location in North Africa) (Fig. 1). ϵ_{Nd} values of the terrigenous fraction at ODP Site 662 over the past 30 kyr range between -11.1 and -12.9 (Fig. 3f). We

Table 1

Radiogenic isotope signatures of North African dust Preferential Source Areas (PSAs). S.D. = standard deviation, n = number of samples included. Data sources: (Abouchami et al., 2013; Bayon et al., 2024; Fielding et al., 2017; Garzanti et al., 2015; Gross et al., 2016; Grousset and Biscaye, 2005; Grousset et al., 1998; Grousset et al., 1992; Guinoiseau et al., 2022; Jewell et al., 2021; Krom et al., 1999; Kumar et al., 2014; Padoan et al., 2011; Revel et al., 2010; van der Does et al., 2018; Zhao et al., 2018 and this study).

PSA name	ϵ_{Nd}	1 S.D.	n	$^{87}\text{Sr}/^{86}\text{Sr}$	1 S.D.	n
Western	-14.4	3.1	67	0.7268	0.0083	39
Atlas	-12.8	1.7	41	0.7258	0.0024	34
MegaChad	-9.7	3.9	52	0.7168	0.0054	32
North-central	-12.5	2.9	28	0.7139	0.0082	13
Eastern	-1.7	3.6	61	0.7065	0.0020	39

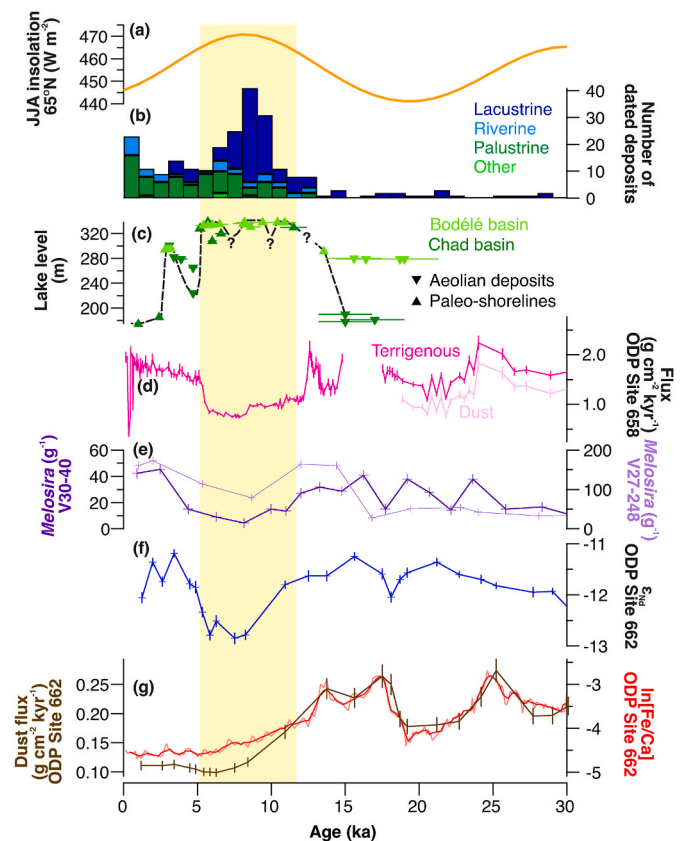


Fig. 3. Megalake Chad and regional climate reconstructions over the past 30 kyr. Yellow shading indicates the timing of the African Humid Period in the Megalake Chad basin. a) Summer (June-July-August) insolation at 65°N from the La2004 orbital solution (orange) (Laskar et al., 2004). b) Age distribution of dated waterlain sediments from within the Megalake Chad basin (Lézine et al., 2011; Manning et al., 2023). c) Reconstructed water levels (black dashed line) of the Chad Basin (dark green) and Bodélé Basin (light green) estimated from aeolian deposits above the water level (inverted triangles) and paleo-shorelines (triangles), redrawn from Armitage et al. (2015). d) Terrigenous (dark pink) and dust (light pink) fluxes from ODP Site 658 with 1σ uncertainty shown by vertical bars (Adkins et al., 2006; Kinsley et al., 2022). e) Concentration of freshwater diatom genus *Melosira* in marine sediment cores V30-40 (dark purple) and V27-248 (light purple) (Pokras and Mix, 1985). Site locations shown on Fig. 1. f) ϵ_{Nd} of the bulk lithogenic fraction of ODP Site 662 sediments. g) Dust flux at ODP Site 662 (brown) with vertical bars indicating 1σ uncertainty and $\ln[\text{Fe}/\text{Ca}]$ of XRF core scanning elemental counts (red), with darker colour indicating 5-pt running mean. New data available in Supplementary Table 2.

therefore interpret this result to represent mixing between the highly dust active Megachad PSA ($\epsilon_{Nd} = -9.7 \pm 3.9$) and the more proximal Western PSA ($\epsilon_{Nd} = -14.4 \pm 3.1$) (Table 1). We do not rule out minor contributions from the North-central, Atlas or Eastern PSAs, but these regions are unlikely to be major sources of terrigenous material to ODP Site 662 because of their lower DSAFs, long transport distances to the Equatorial Atlantic Ocean and less favourable prevailing winds (Fig. 1) (Schepanski et al., 2009, 2017; Washington et al., 2003).

The onset of humid conditions across North Africa associated with the Holocene AHP drove a major increase in the number of dated lacustrine deposits across the Lake Chad basin from ~ 13 ka, which peaked from 10 to 8 ka (Fig. 3; Lézine et al., 2011). Water levels in the Bodélé basin reached a highstand by ~ 11.5 ka, connecting it with Lake Chad to the south to form a megalake (Armitage et al., 2015). A single data point from the Bodélé basin dated to 13.5 ka suggests there may have been sporadic earlier wet intervals, but the main interval of humidity occurred between ca. 11 and 5 ka. Dust fluxes recorded at ODP

Site 662 decreased by more than a factor of two (from 0.24 to 0.1 $\text{g cm}^{-2} \text{ kyr}^{-1}$) between ~ 13.5 ka and 8.5 ka, coincident with a shift in ϵ_{Nd} values from -11.8 to -12.8 (Fig. 3). We attribute this shift in dust provenance to the formation of Megalake Chad during the AHP which shut down dust production in the world's most active hotspot, driving a decrease in the supply of radiogenic dust to the equatorial Atlantic and a shift in our ODP Site 662 record towards the more unradiogenic average compositions of the Western North Africa PSA. We favour this explanation over shifting wind patterns, in agreement with model simulations which suggest that wind directions remained largely unchanged (e.g. Brannon et al., 2000; Murphy et al., 2014; Zhao and Harrison, 2012), and with the stable palaeowind fields documented further north along the African margin (Cole et al., 2009; Crocker et al., 2022; Hooghiemstra et al., 1987).

From ~ 6 to 4 ka, the radiogenic isotope signature recorded at ODP Site 662 shifted back to pre-AHP ϵ_{Nd} values of -12 to -11 . At approximately the same time, lake levels fell rapidly across the Chad basin (Armitage et al., 2015; Kröpelin et al., 2008), with an increase in freshwater diatom fossils deflated from the exposed lake beds recorded in Atlantic Ocean sediments (Pokras and Mix, 1985) (Fig. 3e). We therefore propose that shifts in the provenance of dust (revealed by its neodymium isotope signature) preserved in marine sediments situated underneath the pathway of the winter dust plume can be used as a proxy means of tracking past inundation/desiccation of Megalake Chad on geological timescales.

3.3. Decoupling of dust flux and provenance during Heinrich stadials and the late Holocene

Combined analysis of neodymium isotope measurements and thorium-normalized dust fluxes reveals broadly similar trends in these two proxies, particularly between 20 and 5 ka. However, there are also examples of decoupled proxy behaviour. One example occurs at the end of the AHP, when large-scale desiccation of Megalake Chad induced a marked shift towards more radiogenic ϵ_{Nd} values at ODP Site 662 but we document only a slight increase in dust fluxes (Fig. 3). This modest increase in dust fluxes at ODP Site 662 contrasts with the pronounced end-AHP increase in dust fluxes recorded at more northerly sites (e.g. ODP Site 658, Fig. 3d; Adkins et al., 2006; Kinsley et al., 2022). However, it is consistent with records from other (winter dust plume influenced) equatorial sites stretching across the Atlantic Ocean (Supplementary Fig. 2; Bradtmiller et al., 2007; Francois et al., 1990; Lippold et al., 2016; Ng et al., 2018; Rowland et al., 2021). The low late Holocene dust fluxes recorded across the equatorial Atlantic could be explained by precipitation-induced dust scavenging (e.g. McGee et al., 2007; Rowland et al., 2021; Skinner and Poulsen, 2016; Tiwari et al., 2023). This explanation is consistent with the observation that, even today, the tropical rainbelt lies north of ODP Site 662 during boreal winter despite having shifted/contracted southwards from its mid-Holocene position in response to decreasing northern hemisphere insolation (Collins et al., 2011; Shanahan et al., 2015; Singarayer and Burrough, 2015).

A second example of decoupled proxy behaviour comes from the stadial conditions of the last glacial, when sea surface temperatures in the North Atlantic Ocean were especially cold. During these intervals, very dusty conditions are documented in northwest Africa and attributed both to a strengthening of the northeasterly trade winds (Kinsley et al., 2022; Middleton et al., 2018; Murphy et al., 2014) and a decrease in tropical soil moisture with a proposed $\sim 6^\circ$ southward shift in the Sahara-Sahel boundary (Collins et al., 2013; Hopcroft et al., 2023; Muliya et al., 2008). Our records provide a test of these hypotheses because modern Lake Chad lies at approximately the same latitude as the suggested southern limit of the Saharan desert during Heinrich stadials ($13 \pm 3^\circ \text{N}$, Collins et al., 2013) and the most southerly identified Saharan fossilised sand dunes (14°N , Grove, 1958; Michel and Michel, 1973). Our dust flux and $\ln[\text{Fe}/\text{Ca}]$ records from ODP Site 662 take a similar form to records from further north (e.g. ODP Site 658), with

peaks in dust flux and $\ln[\text{Fe}/\text{Ca}]$ (indicating a high proportion of terrigenous material) at ca. 24.7, 17.3 and 13.5 ka, with ages approximately corresponding to Heinrich stadial 2, Heinrich stadial 1 and the Younger Dryas respectively (Fig. 3). However, there is no strong evidence of a shift in ϵ_{Nd} values across these events to indicate a major change in the location of active dust sources at these times. This result implies that many of the desiccated water bodies that act as key dust source hotspots today (Bakker et al., 2019; Prospero et al., 2002; Washington et al., 2003) were already at least seasonally dry and dust-active under baseline glacial conditions. Thus, any further decreases in soil moisture and/or increases in wind strength associated with cold North Atlantic sea surface temperatures (e.g. Hopcroft et al., 2023; Shanahan et al., 2012; Weldeab et al., 2007) did not have a major influence on the spatial distribution of dust sources. In this interpretation, the increase in dust flux recorded at ODP 662 was driven by a combination of increased soil erodibility and a strengthening of north-easterly winds during stadial periods (and/or increase in gustiness) (Kinsley et al., 2022; Liu et al., 2014; McGee et al., 2010; Murphy et al., 2014), resulting in greater deflation of existing dust sources and export to the eastern equatorial Atlantic.

4. Summary and conclusions

The detrital fraction of equatorial Atlantic sediments from ODP Site 662 provides a continuous record of windblown dust from North Africa and its neodymium isotopic signature preserves a proxy record of the inundation/desiccation of the endorheic Lake Chad basin. The Bodélé Depression, the dustiest place on Earth, has a comparatively radiogenic neodymium isotope signature for western/central North Africa because of riverine input of fine-grained sediments from the young volcanic Tibesti Mountains during past intervals of humidity. When the Lake Chad basin is arid, dust fluxes from the basin are high, with a radiogenic neodymium isotope signature imprinted onto windblown dust exported to the eastern equatorial Atlantic by strong northeasterly trade winds. During the mid-Holocene African humid period, when a megalake occupied much of the Lake Chad basin, we record a shift to more unradiogenic isotope values and low Th-normalized dust fluxes signalling a shutdown of the main dust sources in the Lake Chad basin. Our approach of combining analysis of neodymium isotopes and dust fluxes allows us to separate out the influences of transport processes and sediment availability driven by regional hydroclimate on the export of aeolian sediments from the dustiest place on Earth using continuous sedimentary archives which have the potential to preserve records over thousands to millions of years.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quascirev.2025.109503>.

Data availability

All new data published in this study and compiled radiogenic isotope data are available as supplementary data files and at <https://doi.org/10.5281/zenodo.14795870>.

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