

Arabian hydroclimate and hominin population dynamics over the last 500,000 years

Corresponding Author: Dr Zhaoxia Jiang

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

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Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

Review of: Arabian hydroclimate and hominin population dynamics over the last ~500,000 years

Introduction

This study reports new geochemical datasets from a western Indian Ocean core (CJ02-08) that are interpreted as Arabian Peninsula aridity proxies spanning the last approx. 500 kyr. A composite aridity proxy is then compared with other regional and global climate proxies, and with the archaeological record of the Arabian Peninsula, to infer that hominin occupation and expansion occurred during periods of enhanced monsoon precipitation.

Dust Proxy

Demonstrating an Arabian dust source within CJ02-08 is key to the interpretation of the proxies. This is achieved in the strontium and neodymium isotope plot (Figure S3). However there are just 6 samples analysed from across the core (Table S1). It is a big leap to suggest that "terrigenous source regions remained unchanged over the past 500 kyr" - it is quite possible that repeated shifts in dust sources have been missed.

Supplementary Note 3 discusses how the magnetic mineral and trace element records can be interpreted as dust proxies. However, it's not immediately clear how these measurements were transformed into the "dust index" shown in figure 3b and how this relates to the PCA shown in Figure S6. From visual inspection, it looks like the dust index is a combination of panels b-e from Figure 2, but this needs to be explained in more detail in the text.

Previous Publications

Some of the magnetic measurements for core CJ02-08 were previously published in Chen et al. (2023), in combination with measurements from the nearby core CJ02-01 (Zhou et al., 2024). Chen et al. (2003) established a 500 kyr chronology for Core CJ02-08 and a 200 kyr chronology CJ02-01 as part of a regional stack. The chronological framework was constructed by "wiggle-matching" the magnetic records against the PISO-1500 (Channell et al., 2009) and LR04 $\delta^{18}O$ (Lisiecki and Raymo, 2005) global stacks. The age model was produced using 22 tie points for CJ02-08; it shows a relatively static accumulation rate and no inferred hiatuses. As far as I can tell from the publications there are no independent age controls for CJ02-08, such as biostratigraphy or radiometric ages.

Age control of the palaeoclimate proxies

It is surprising that there is no discussion of the Chen et al. (2023) age model in the manuscript, other than Figure S2 which is a modified version of Figure 8b from Chen et al. (2023). When comparing the two plots, there are some unexplained discrepancies between data points (only 16 tie points in this study, 22 tie points in the previously published work). It is important to acknowledge the uncertainties inherent in the age model, especially when undertaking the time-series analysis (Figure 2) and when comparing with other regional palaeoclimate records (Figure 3).

I'm curious as to why in this study the authors don't attempt to re-tune the age model. The U/Th dated Arabian speleothems from Nicholson et al. (2020) grow during pluvials. They don't always match up with the CJ02-08 Dust Index in Figure 3; assuming they should match, the age model could be tuned to these pluvials. Alternatively, the lack of matching needs to be explained.

Time Series Analysis

Time series analysis features in Figure 2 and is used to infer precessional control on the dust record. However, as discussed above, the CJ02-08 time series was tuned to the PISO-1500 and LR04 records (Chen et al., 2023), which both contain strong eccentricity and precession signals. It would be very helpful to see the spectral analysis performed on the raw CJ02-08 depth series, prior to tuning – does this reduce the spectral power?

Significant spectral peaks are identified using a first-order autoregressive (AR1) noise model to compute the 90% and 95% confidence levels. These significant peaks (e.g. 54 kyr) are labelled in Figure 2, although few of them are recognised orbital frequencies. The 29 kyr cycle is perhaps close enough to the 23 kyr precession cycle to be considered an orbital cycle, although this needs to be discussed in the text. These spectral peaks only just exceed the 90% confidence level – the 95% confidence level is not shown in Figure 2, perhaps because the peaks do not exceed this background level? Recent studies show that the false detection of peaks is common in cyclostratigraphy (Weedon, 2022) and that the use of more robust False Discovery Rate (FDR) backgrounds is recommended. If this method is used for CJ02-08, it's likely that most of the observed peaks will no longer be significant.

Spatio-temporal distribution of archaeological record

In the next stage of the manuscript, the authors compare their dust record with the archaeological and palaeoenvironmental (primarily lake deposits) records of the Arabian Peninsula. In Figure 4c they do this by producing a Kernel Density Estimate (KDE) of dated archaeological and palaeoenvironmental proxies. The KDE has peaks at every ~100 kyr, of decreasing magnitude, although the significance of these peaks is unclear, as there is no background included in this plot. It is likely that the archaeological (and palaeoenvironmental) record decays exponentially with time, as the preservation and discovery potential is so much greater for younger archaeology. Similar trends are found for speleothem preservation, and authors recommend applying exponential backgrounds to KDEs (Scroton et al., 2016; Weij et al., 2020). It may be the case that in Figure 4c only the largest peak (at ~75ka) is significant.

The two dimensional KDE in Figure 4b shows that most of the Arabian Peninsula archaeological sites are from the Levant and are relatively young (<100 ka). In Figure 5 most the Levant is reconstructed as a sub-Mediterranean climate (present day and Eemian) so is not directly relevant to the discussion of desert environments. If the Levantine sites are removed from the dataset, there is not enough evidence from the Arabian Peninsula proper to assign the archaeology to discrete periods of the past.

Summary

This manuscript is wide in scope and broadly plausible, but there are a number of issues that the authors seem to brush over. The uncertain chronology of the dust record and the presence (or more likely absence) of significant spectral peaks renders the interpretation of orbitally forced pluvial periods across Arabia as speculative. While it's plausible that hominin populations expanded during pluvial periods, there is not enough evidence presented to demonstrate this. I would recommend that this work is published in a longer-format journal where the authors can devote more discussion to the interpretation of their record.

References:

- Channell, J.E.T., Xuan, C. & Hodell, D.A., 2009. Stacking paleointensity and oxygen isotope data for the last 1.5 myr (PISO-1500). *Earth planet. Sci. Lett.*, 283 (1-4), 14–23.
- Chen, L., Zhou, L., Liu, J.B., Yin, Z.X., Zhang, J.L., Guan, Y.L., Chen, L., Zhang, Y.Z., Hu, Y.W., Liu, Y., Jiang, Z.X., 2023. A stacked record of relative paleointensity for past 500 ka from western equatorial Indian Ocean sediments. *Geophys. J. Int.* 235, 2540–2555.
- Lisiecki, L.E. & Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$ records, *Paleoceanography*, 20, 1–17.
- Nicholson, S.L. et al. Pluvial periods in Southern Arabia over the last 1.1 million-years. *Quat. Sci. Rev.* 229, 106112 (2020).
- Scroton, N., Gagan, M. K., Dunbar, G. B., Ayliffe, L. K., Hantoro, W. S., Shen, C.-C., Hellstrom, J. C., Zhao, J., Cheng, H., Edwards, R. L., Sun, H., Rifai, H. (2016). Natural attrition and growth frequency variations of stalagmites in southwest Sulawesi over the past 530,000 years. *Palaeogeography, Palaeoclimatology, Palaeoecology*, Volume 441, Part 4, Pages 823-833.
- Weedon, G. P. (2022). Problems with the current practice of spectral analysis in cyclostratigraphy: Avoiding false detection of regular cyclicity, *Earth-Science Reviews*, 235, 104261.
- Weij, R., Woodhead, J., Hellstrom, J., Sniderman, K. (2020). An exploration of the utility of speleothem age distributions for palaeoclimate assessment. *Quaternary Geochronology*, 60, 101112.
- Zhou, Liang. et al. Aridity record of the Arabian Peninsula for the last 200 kyr: environmental magnetic evidence from the western equatorial Indian Ocean. *Quat. Sci. Rev.* 341, 108876 (2024).

Reviewer #2

(Remarks to the Author)

This manuscript presents a multi-proxy dust record from the Western Equatorial Indian Ocean, reflecting dust activity and environmental conditions in the arid regions of Arabia. The authors utilize demographic and ecological data to estimate hominin populations in these regions. The correlation between the two datasets leads to the conclusion that significant hominin population expansions occurred mainly during the Green Arabia periods (GAPs). Thus, this study provides the first paleoenvironmental records with orbital resolution for the Arabian arid region, complemented by extensive archaeological findings, and establishes a strong link between climatic changes and hominin expansion and dispersal. Additionally, this study offers a comprehensive understanding of environmental dynamics at orbital timescales. I strongly support the publication of these results in NC; however, the manuscript could benefit from improvements in organization and clarity. I suggest a moderate revision.

My main concerns are as follows:

1. The structure of the text could be refined. For instance, the paragraph (Lines 60-75) should conclude with the main focus of this study: the linkage between environmental conditions and hominin dynamics. In the section titled "Dust Content Changes Over the Past 500 kyr," it is not effective to present results proxy by proxy.
2. A fundamental assumption of this study is that the core deposits primarily consist of dust input. Evidence supporting this assumption should be summarized in the main text.
3. How was the timescale established?
4. As the authors acknowledge that fluvial terrigenous and biogenic materials also contribute to sediment composition, it should be clarified how these non-aeolian materials affect the changes in Mg/Al and Ti/Ca ratios.

Specific comments:

- Line 61: It would be better to specify the region's name rather than using "in area..."
- Lines 67-68: Is there evidence supporting the statement that "the debate remains about whether the Arabian Peninsula experienced orbitally-paced GAPs before the late Pleistocene"? It seems that the current climate regime has formed much earlier than the late Pleistocene.
- Lines 84-89: The logic here may be difficult for general readers to follow. The changes in hematite and goethite should clearly link to dust activity.
- Lines 90-91: Which proxy indicates that these periods were humid?
- Lines 102-112: This paragraph should be moved after the results of all proxies.
- Lines 161-163: When did high dust contents occur?
- Lines 176-182: This paragraph discusses the role of obliquity. I believe the authors go too far with this discussion. If this is the case, please further explain how insolation maxima and obliquity maxima co-drive changes in monsoons.
- Line 245: 1000%?
- Lines 249-251: Please rephrase the sentence regarding "repeated expansion and contraction during GAPs."
- Lines 292-305: I do not think this paragraph should revert to addressing dust activity in this section.
- Fig. 2g: Please verify the data for Xfd%.
- Fig. 3b: How was the dust index curve generated?

Version 1:

Reviewer comments:

Reviewer #2

(Remarks to the Author)

I have reviewed the rebuttal letter and the revised manuscript. I am satisfied with the responses and the revisions made. The revision has significantly improved the clarity of the age model and proxy interpretation, as well as the overall structure and readability. The evidence presented provides a solid basis for the environmental interpretation and its influence on hominin occupations and dispersals in the Arabian Peninsula. I am happy to recommend publication of the paper in its current form.

Reviewer #3

(Remarks to the Author)

The manuscript entitled "Arabian hydroclimate and hominin population dynamics over the last ~500,000 years" offers an interesting insight into the palaeoenvironmental conditions of the Arabian region during the latter half of the Middle Pleistocene. The results are based on data retrieved from a marine core (CJ02-08) in the Indian Ocean, and their interpretation helps refine the development of the 'Green Arabia' periods (GAPs). Furthermore, this palaeoenvironmental information is correlated with the available archaeological record for the same geographical region.

The manuscript's premise is compelling and aligns with recent publications that statistically model human occupation events based on palaeoclimate data. Regarding the processing and interpretation of the palaeoenvironmental data, I see no major issues, the approach appears robust and methodologically sound. However, the correlation between the palaeoenvironmental data and the archaeological record is more problematic. According to the data presented in the main text and supplementary material, most of the archaeological sites do not originate strictly from the Arabian region itself. Instead, they are concentrated along the northern Mediterranean coast, where environmental conditions differed significantly from those in the interior of the Arabian Peninsula. Furthermore, the archaeological data used have been "anonymised", in the sense that their cultural attribution is not discussed; that is, Acheulean, Achelo-Yabrudian, and Middle Palaeolithic contexts are analysed in the same manner without any critical distinction. It is worth noting that these technocomplexes were produced by different hominin species, each possessing specific characteristics and behavioural adaptations that have not been taken into account.

In many cases, the chronological dates have large margins of error and are utilized without prior critical evaluation. Given

this baseline data, while the conclusions presented in the manuscript are supported by the model, they could equally be questioned due to the lack of robustness in the archaeological data. Crucially, the conclusions presented are not particularly novel, as they simply suggest that human expansion events correspond to periods of more favourable environmental conditions. Could one expect otherwise?

I believe that before publication can be considered, the archaeological data must be integrated with much greater depth, rather than serving as a mere supplement to the interpretation of palaeoclimate proxy results. A thorough preliminary discussion of the archaeological data, their cultural attribution, and the chronological framework is essential.

Version 2:

Reviewer comments:

Reviewer #3

(Remarks to the Author)

The authors have revised and updated the manuscript, successfully addressing several of its main shortcomings. Consequently, I consider that the text is now suitable for publication.

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Reply to review comments

Reviewer #1:

This study reports new geochemical datasets from a western Indian Ocean core (CJ02-08) that are interpreted as Arabian Peninsula aridity proxies spanning the last approx. 500 kyr. A composite aridity proxy is then compared with other regional and global climate proxies, and with the archaeological record of the Arabian Peninsula, to infer that hominin occupation and expansion occurred during periods of enhanced monsoon precipitation.

Thank you for this positive feedback. We address the suggestions below. In the revised manuscript, changes are indicated in red lettering.

Dust Proxy

Q1: *Demonstrating an Arabian dust source within CJ02-08 is key to the interpretation of the proxies. This is achieved in the strontium and neodymium isotope plot (Figure S3). However, there are just 6 samples analysed from across the core (Table S1). It is a big leap to suggest that “terrigenous source regions remained unchanged over the past 500 kyr” - it is quite possible that repeated shifts in dust sources have been missed.*

To address this key issue and to improve our provenance analysis, we added 6 new Sr-Nd isotope analyses for core CJ02-08 for stratigraphic intervals that were sampled less densely. These analyses were completed using the same analytical methods and instrumental conditions as the original experiments to avoid methodological biases. The expanded Sr-Nd isotope dataset (12 samples in total) is shown in the revised Figure S3, with data for new samples added to a revised Table S1. These results enable re-validation of the dust source for core CJ02-08 and temporal variations of terrigenous source regions. Nd and Sr data for the cleaned bulk terrigenous fraction align closely with Arabian compositions, with relatively stable and low radiogenic Sr and less negative radiogenic Nd (Figure R1). This indicates that sediment provenance has been uniform throughout the investigated period. Relevant results and discussion are updated in the revised Supplementary Information.

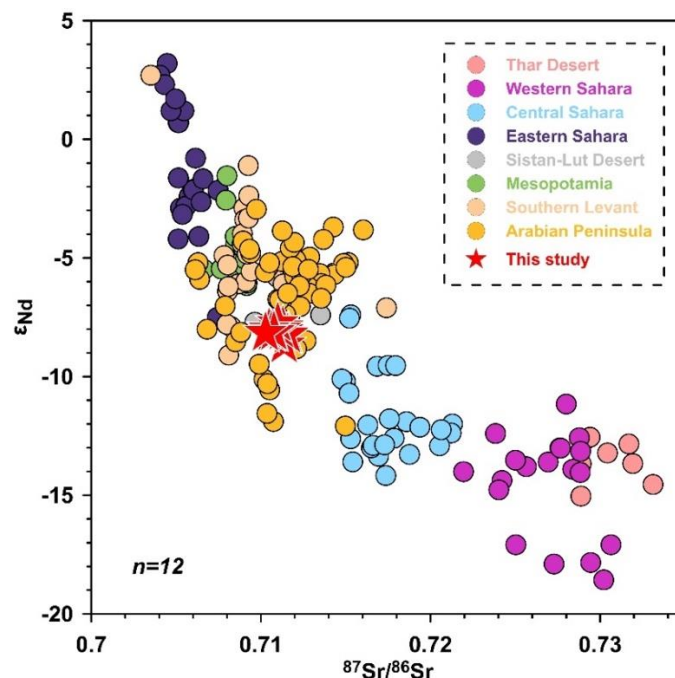


Figure R1. Sr-Nd radiogenic isotope signature of core CJ02-08 lithic fraction compared to values for potential source areas.

Q2: *Supplementary Note 3 discusses how the magnetic mineral and trace element records can be interpreted as dust proxies. However, it's not immediately clear how these measurements were transformed into the "dust index" shown in figure 3b and how this relates to the PCA shown in Figure S6. From visual inspection, it looks like the dust index is a combination of panels b-e from Figure 2, but this needs to be explained in more detail in the text.*

Sorry. We have revised relevant content to elaborate on the procedure as follows. We propose four dust proxies, including an environmental magnetic parameter ($IRM_{1T@AF80mT}$), diffuse reflectance spectroscopy (I_{Gt}), and geochemical element ratios (Mg/Al, Ti/Ca). Each is linked independently to eolian dust variability within the source area and atmosphere. These independent eolian dust proxies are stacked to derive a more robust, combined record of dust variability. Stacking was accomplished by normalizing each record to unit variance, and averaging (Caley et al., 2011; Clemens & Prell, 2003). The Min-Max normalization method was adopted for data standardization, which is a linear transformation of original data that scales normalized results to the 0 to 1 range. The corresponding transformation function is: $x^* = (x - \min) / (\max - \min)$, where max and min represent maximum and minimum data values, respectively. The dust index is defined by the arithmetic mean of normalized $IRM_{1T@AF80mT}$, I_{Gt} , Mg/Al, and Ti/Ca ratios, with associated errors calculated as the standard deviation. We have added this description in the *Climate impacts on hominin occupation and dispersals* section of the revised manuscript (Line 215-219). Further details are added into Supplementary Information Note 6.

Previous Publications

Q3: *Some of the magnetic measurements for core CJ02-08 were previously published in Chen et al. (2023), in combination with measurements from the nearby core CJ02-01 (Zhou et al., 2024). Chen et al. (2003) established a 500 kyr chronology for Core CJ02-08 and a 200 kyr chronology CJ02-01 as part of a regional stack. The chronological framework was constructed by "wiggle-matching" the magnetic records against the PISO-1500 (Channell et al., 2009) and LR04 $\delta^{18}O$ (Lisiecki and Raymo, 2005) global stacks. The age model was produced using 22 tie points for CJ02-08; it shows a relatively static accumulation rate and no inferred hiatuses. As far as I can tell from the publications there are no independent age controls for CJ02-08, such as biostratigraphy or radiometric ages.*

The most common methods for dating marine sediment cores cannot be applied to these sediments over the ~100-500 kyr age range. For example, although foraminifera are present, shell fragmentation is too high to enable $\delta^{18}O$ analyses. Relative paleointensity (RPI) variations, which enable assessment of continuous geomagnetic field intensity evolution up to millennial-multimillennial resolution, can then be useful for high-resolution Brunhes Chron chronostratigraphy (Tauxe, 1993). Magnetic excursions associated with RPI minima have synchronous global manifestation, which strengthens their usefulness in Quaternary stratigraphy (Channell et al., 2020). Like geomagnetic reversals, RPI variations are suitable for global correlation because the signal is dominated by the global magnetic field. Such a globally coherent geophysical signal is useful for dating marine sediments because it is independent of seawater chemistry and, therefore, provides independent dating compared to paleoceanographic proxies (e.g., foraminiferal $\delta^{18}O$). Many stacked Brunhes Chron paleointensity curves, such as Sint-800 (0-800 ka, Guyodo & Valet, 1999), NAPIS-75 (0-75 ka, Laj et al., 2000), NOPAPIS-250 (0-250 ka, Yamamoto et al., 2007), and PISO-1500 (0-1500 ka, Channell et al., 2009), provide target curves for correlation of other RPI records to a global chronology.

Also, environmental magnetic parameters mainly reflect magnetic mineral concentration and grain size variations, which are controlled by the surrounding environments and climate (Thompson & Oldfield, 1986). Correlation of magnetic parameters with marine $\delta^{18}O$ records is well established for

building sedimentary chronological frameworks, such as in the Atlantic (Channell et al., 2012) and Pacific oceans (Yamamoto et al., 2007). Therefore, Chen et al. (2023) presented new RPI and environmental magnetic records for cores from the western equatorial Indian Ocean to construct a reasonable chronological framework for the studied cores, which we use here as a basis for understanding dust inputs to the core site. To improve the chronology, we also correlated the Ba/Ti ratio to the LR04 global $\delta^{18}\text{O}$ stack in the revised manuscript (See Response to Q5 for details).

Age control of palaeoclimate proxies

Q4: *It is surprising that there is no discussion of the Chen et al. (2023) age model in the manuscript, other than Figure S2 which is a modified version of Figure 8b from Chen et al. (2023). When comparing the two plots, there are some unexplained discrepancies between data points (only 16 tie points in this study, 22 tie points in the previously published work). It is important to acknowledge the uncertainties inherent in the age model, especially when undertaking the time-series analysis (Figure 2) and when comparing with other regional palaeoclimate records (Figure 3).*

Sorry. Please see our response above to Q3. A total of 12 convincing age control points were initially identified by correlation of our RPI curves to global curves. Another 10 age control points were then assigned by correlating magnetic grain-size variations with the LR04 global $\delta^{18}\text{O}$ stack (Lisiecki & Raymo, 2005) to improve the age model resolution. This now provides 22 age tie points for core CJ02-08. Some uncertain age control points from Chen et al. (2023) were eliminated here, so we used only 16 tie points in the reviewed version of this paper compared to 22 in Chen et al. (2023).

Q5: *I'm curious as to why in this study the authors don't attempt to re-tune the age model. The U/Th dated Arabian speleothems from Nicholson et al. (2020) grow during pluvials. They don't always match up with the CJ02-08 Dust Index in Figure 3; assuming they should match, the age model could be tuned to these pluvials. Alternatively, the lack of matching needs to be explained.*

Following this valuable suggestion, we re-evaluated and improved the core CJ02-08 age model. Although magnetic grain-size (ARM/SIRM) variations are similar to the LR04 global $\delta^{18}\text{O}$ stack over the last 500 ka (Chen et al., 2023), some age control points obtained by correlating ARM/SIRM to the $\delta^{18}\text{O}$ stratigraphy are uncertain. To improve the initial age model of Chen et al. (2023), glacial-interglacial cycles in elemental abundance ratios (e.g., Ba/Ti, Ba/Al), rather than environmental magnetic parameters, were used to refine the age model. Bulk Ba/Ti or Ba/Al can enable evaluation of relative export productivity changes (Murray et al., 2000). Relative biogenic Ba abundance increases with export production in interglacial intervals, and have been tentatively correlated with $\delta^{18}\text{O}$ records (Des Combes et al., 1999; Divakar Naidu & Malmgren, 1999). Downcore Ba/Ti variability for core CJ02-08 is comparable to Ba/Al and Ba variations from adjacent cores, both of which have been used to constrain core chronologies (Des Combes et al., 1999; Divakar Naidu & Malmgren, 1999). We assume Ba/Ti to represent a biological/terrestrial input ratio for our study site, which varies with glacial/interglacial productivity changes due to global ice volume variations. A high-resolution core CJ02-08 Ba/Ti record can be correlated to the global LR04 $\delta^{18}\text{O}$ stack (Lisiecki & Raymo 2005), which improves the correlation (Chen et al., 2023). Each deglacial transition is marked by transient sedimentary biogenic Ba accumulation increases (Des Combes et al., 1999; Divakar Naidu & Malmgren, 1999), which enabled us to add 7 age tie points (Figure R2b). Combined with age control points from RPI correlation (Chen et al., 2023) to the PISO-1500 RPI stack (Figure R2a), we refined the core CJ02-08 age model using linear interpolation between age tie points. The age-depth model is almost linear (Figure R2c) and well constrained because of the reasonable number of reliable tie points. Sedimentation rates vary between 0.6 and 1.6 cm/kyr with mean of 1.0 cm/kyr,

which is consistent with those documented for other western equatorial Indian Ocean sediment cores (Des Combes et al. 1999; Meynadier et al. 1994).

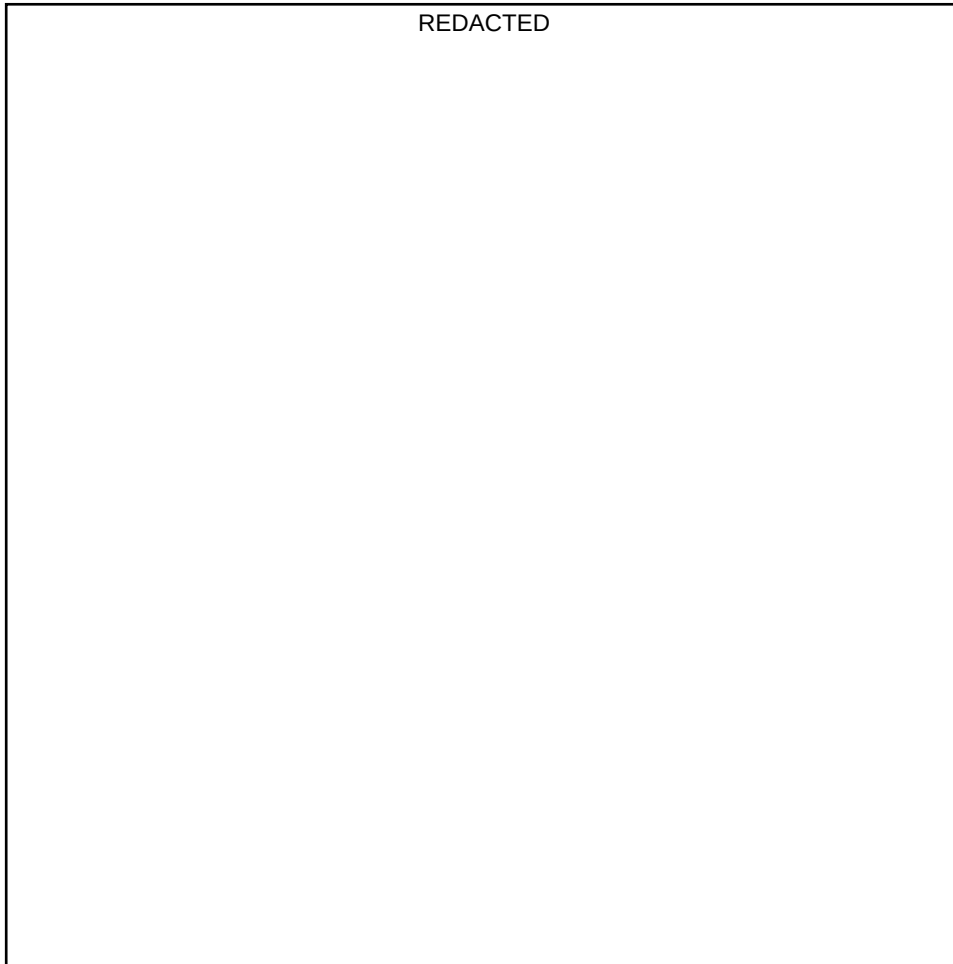


Figure R2. Age model for core CJ02-08. (a) RPI records ($RPI = NRM_{30mT}/SIRM_{30mT}$) for core CJ02-08 (Chen et al., 2023) matched with the PISO-1500 stack (Channell et al., 2009). (b) Ba/Ti of core CJ02-08 matched with the marine oxygen isotope stack (LR04) (Lisiecki & Raymo, 2005). (c) Depth-age plot and sediment accumulation rates (SARs) for core CJ02-08. Fifteen age tie points were obtained using the main geomagnetic minima (green circles) and correlating abrupt Ba/Ti increases to each major glacial termination (red crosses), indicated by red dashed lines. The black dashed line represents a linear correlation between age and depth.

We have added details of age model refinement for core CJ02-08 in the revised manuscript (Lines

88-95) and supplementary information Note 2, respectively. In our new chronological framework, Green Arabia Periods (GAPs) recorded by the core CJ02-08 dust index date to ~10, 80, 105, 125, 205, 245, 315, 330, 410, and 480 ka. Arabian speleothem growth during pluvials (Nicholson et al., 2020) match Dust Index minima for core CJ02-08 for most GAPs with a few mismatches (Figure R3). For example, the Eemian GAP had moderately low dust contents unlike other GAPs (Figure R3) even though available speleothem and lacustrine/alluvial sediment evidence indicate that it was likely the wettest GAP for at least the last 250 kyr (Nicholson et al., 2020; Parton et al., 2018). Arabian dust is transported to the western equatorial Indian Ocean by winds involved in monsoonal circulation (e.g., the shamal), so we interpret that enhanced Eemian GAP shamal intensity (Clemens & Prell, 2003) facilitated dust mobilization from Arabian interior desert areas from $>28^{\circ}\text{N}$, which is beyond the reach of the monsoon front (Zhou et al., 2024). The influence of these arid areas partly counteracted the role of vegetation in diminishing Arabian interior dust mobilization south of $\sim 28^{\circ}\text{N}$.

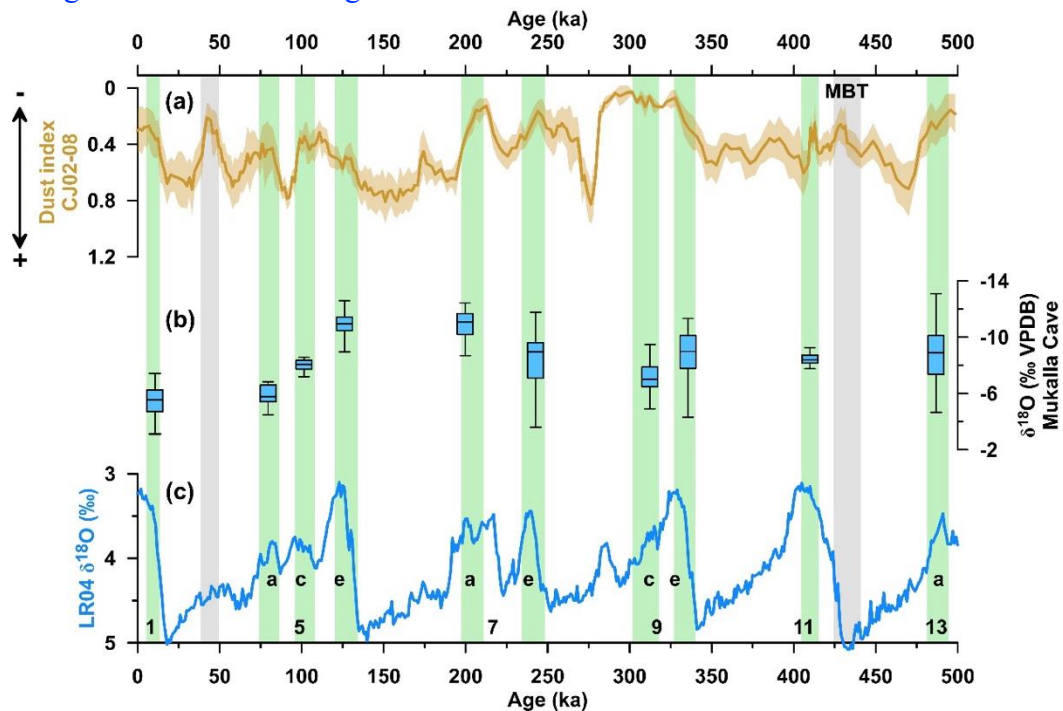


Figure R3. (a) Dust index for core CJ02-08 (this study), (b) $\delta^{18}\text{O}$ records for Mukalla Cave speleothems (Nicholson et al., 2020), and (c) LR04 benthic $\delta^{18}\text{O}$ stack (Lisiecki & Raymo, 2005).

Moreover, lack of speleothem growth during the Mid-Brunhes Transition (~ 430 - 450 ka) and a clear dust minimum (Figure R3) suggest that the monsoons were considerably weaker at this time and that they did not penetrate into the Arabian Peninsula to create widespread “green” landscapes (Nicholson et al., 2020). Precipitation may not have been sustained or intense enough to substantially impact Arabian environments. Hence, the dust minimum can be alternatively attributed to wet deposition related to northward ISM penetration. Rapid Antarctic ice-sheet expansion at the MIS 12/11 transition led to increased Southern Hemisphere meridional temperature gradients and more energetic trade winds with cross-equatorial flow (McKay et al., 2012; Struve et al., 2020). Northward ITCZ shifts during these periods also act as a barrier to partly remove airborne particles through heavy rainfall (Reimi & Marcantonio, 2016; Seo et al., 2021). Another clear dust minimum without speleothem growth at ~ 44 ka (Figure R3) can also be attributed to wet deposition related to northward ISM penetration (Clemens & Prell, 2003). The ISM can only penetrate as far as southern Arabia (Parton

et al., 2018; Timmermann & Friedrich, 2016); glacial boundary forcing prevented this interstadial from becoming a GAP. This explanation regarding dust variability is indicated by red lettering in the revised manuscript (Lines 133-142 and Lines 181-190).

Time Series Analysis

Q6: *Time series analysis features in Figure 2 and is used to infer precessional control on the dust record. However, as discussed above, the CJ02-08 time series was tuned to the PISO-1500 and LR04 records (Chen et al., 2023), which both contain strong eccentricity and precession signals. It would be very helpful to see the spectral analysis performed on the raw CJ02-08 depth series, prior to tuning – does this reduce the spectral power?*

We agree. As is well known, the chronologies of long marine, loess, and ice core records are often based on orbital tuning (Cheng et al., 2022), which may introduce periodicities from the target curve (PISO-1500 and LR04 stack). To assess the authenticity of orbital periodicities, we performed spectral analysis on the raw depth-series data for core CJ02-08 using the Astrochron R package (Meyers, 2014). These results reveal pervasive depth cycles of ~90-100 cm, ~41-44 cm, and ~19-23 cm (Figure R4), with significant spectral power that exceeds the 95% confidence level for red noise, with no meaningful relative power reduction compared to the tuned age-series. Considering a 1.0 cm/ka sedimentation rate, these depth cycles correspond to 88-98 kyr, 40-43 kyr, and 19-23 kyr, which correspond well to orbital eccentricity (~100-kyr), obliquity (~41 kyr), and precession (~23 kyr) cycles, respectively, consistent with those identified in the tuned age-series. This confirms that orbital (especially eccentricity and precession) periodicities in the CJ02-08 dust record are inherent to the original stratigraphic signal rather than being a tuning artifact. We added a new Figure S9 to the Supplementary Information with a power spectral density plot of the untuned depth-series dust record to highlight the statistical significance of the orbital signals. It explicitly distinguishes spectral results for the untuned depth-series and the tuned age-series with consistent orbital periodicities between the two (Figure R4 & R5). Details are added to Supplementary Information Note 5.

REDACTED

Figure R4. Power spectral estimates for depth-series dust proxies using the Astrochron R package (Meyers, 2014) with 99%, 95%, and 90% confidence level curves shown.

***Q7:** Significant spectral peaks are identified using a first-order autoregressive (AR1) noise model to compute the 90% and 95% confidence levels. These significant peaks (e.g. 54 kyr) are labelled in Figure 2, although few of them are recognised orbital frequencies. The 29 kyr cycle is perhaps close enough to the 23 kyr precession cycle to be considered an orbital cycle, although this needs to be discussed in the text. These spectral peaks only just exceed the 90% confidence level – the 95% confidence level is not shown in Figure 2, perhaps because the peaks do not exceed this background level? Recent studies show that the false detection of peaks is common in cyclostratigraphy (Weedon, 2022) and that the use of more robust False Discovery Rate (FDR) backgrounds is recommended. If this method is used for CJ02-08, it's likely that most of the observed peaks will no longer be significant.*

We appreciate this insightful comment, which we address in the following three ways.

(1) Clarification of the 90% confidence level in Figure 2. In our Acycle-based spectral analysis, all identified orbital and secondary cycles (including 54 kyr and 29 kyr peaks noted by the reviewer) have power that exceeds the 95% red noise confidence level. The 90% and 95% confidence level

curves overlap closely, so we just showed the 90% level. To highlight the spectral peaks, we show the 95% confidence level in the revised Figure 2.

(2) Upgraded spectral analysis workflow with rigorous false positive control. To reduce the risk of false cycle detection (as highlighted by Weedon (2022)) to address this concern, we used a more rigorous workflow (in the Astrochron R package) (Meyers, 2014) for spectral analysis—with built-in safeguards against Type I (false positive) errors (Line 406-415). We now state that while use of >99% confidence levels reduce Type I errors, they incur a high risk of Type II errors (failing to detect genuine cyclicity). To balance minimization of Type I errors and avoidance of excessive Type II (false negative) errors (Kemp, 2016), we employ the 95% red noise confidence level combined with explicit false positive testing for all spectral peaks—this stringent threshold far exceeds the original 90% level and addresses concerns about false detection raised by the reviewer.

(3) Revised interpretations of spectral peaks based on upgraded analysis. Consistent with the review comment, the more rigorous Astrochron-MTM analysis with 95% confidence level and false positive testing has refined interpretation of our spectral peaks. The 54 kyr and 35 kyr peaks identified using the Acycle software are not statistically significant in the revised analysis (Figure R4 & R5) and have been removed from the revised Figure 2. Notably, the 29 kyr peak remains clearly resolved and spatially separated from the orbital precession (23 kyr) band above the 99% red noise confidence level in the primary spectral analysis (Figure R5). It also passes the explicit false positive test with a confidence level above 90% (Figure R6), which confirms that the 29 kyr peak is not a false positive. We have added discussion (Lines 191-195) to address its distinction from the 23 kyr precession cycle and potential palaeoclimatic implications. The above revisions, including methodological upgrades, figure and caption modifications, refined spectral interpretations, and discussion of *Spectral analysis of dust records* in the Supplementary Information Note 5, are included in the revised manuscript.

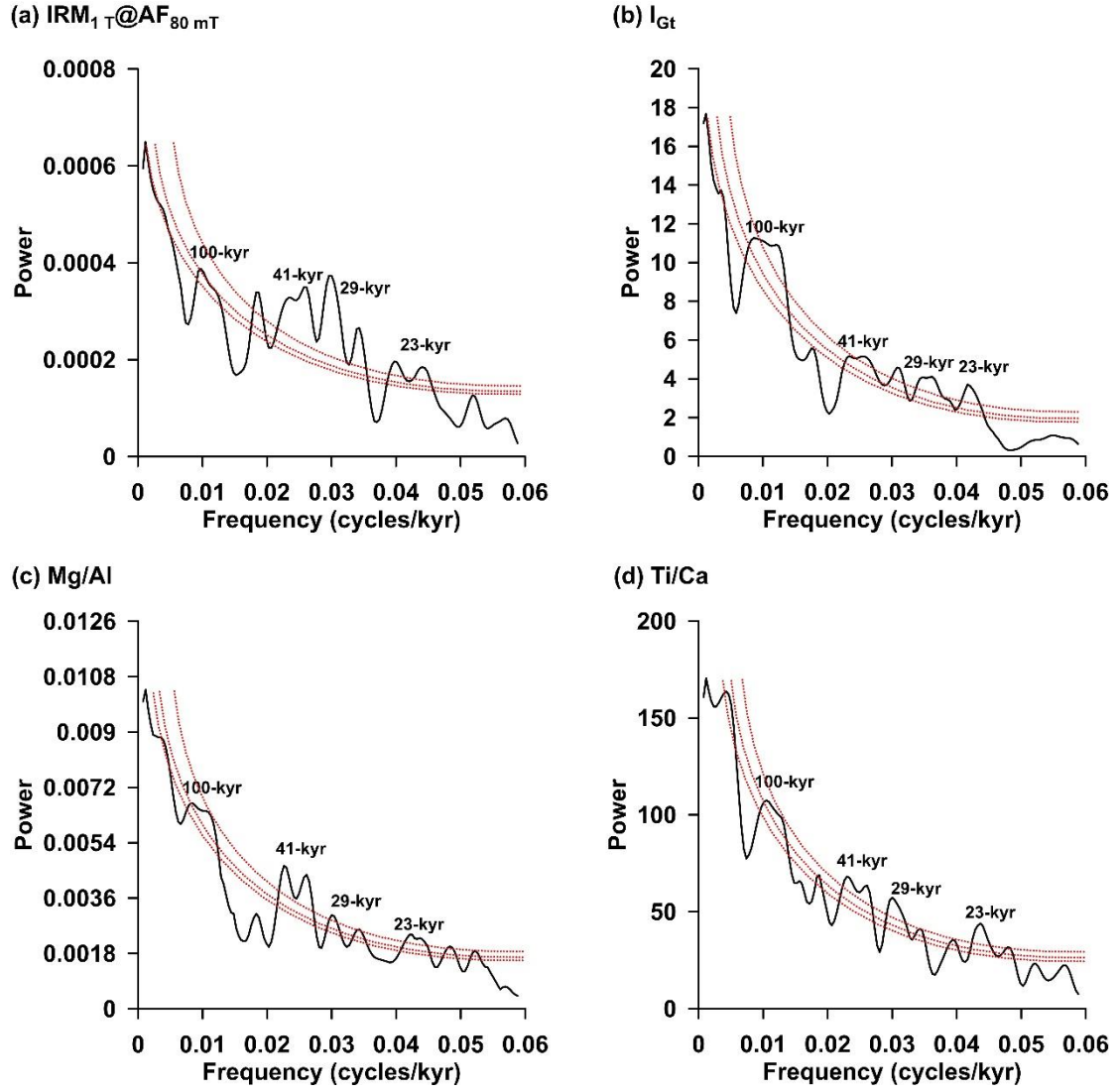


Figure R5. Power spectral estimates for age-series dust proxies using the Astrochron R package (Meyers, 2014) with 99%, 95%, and 90% confidence level curves shown.

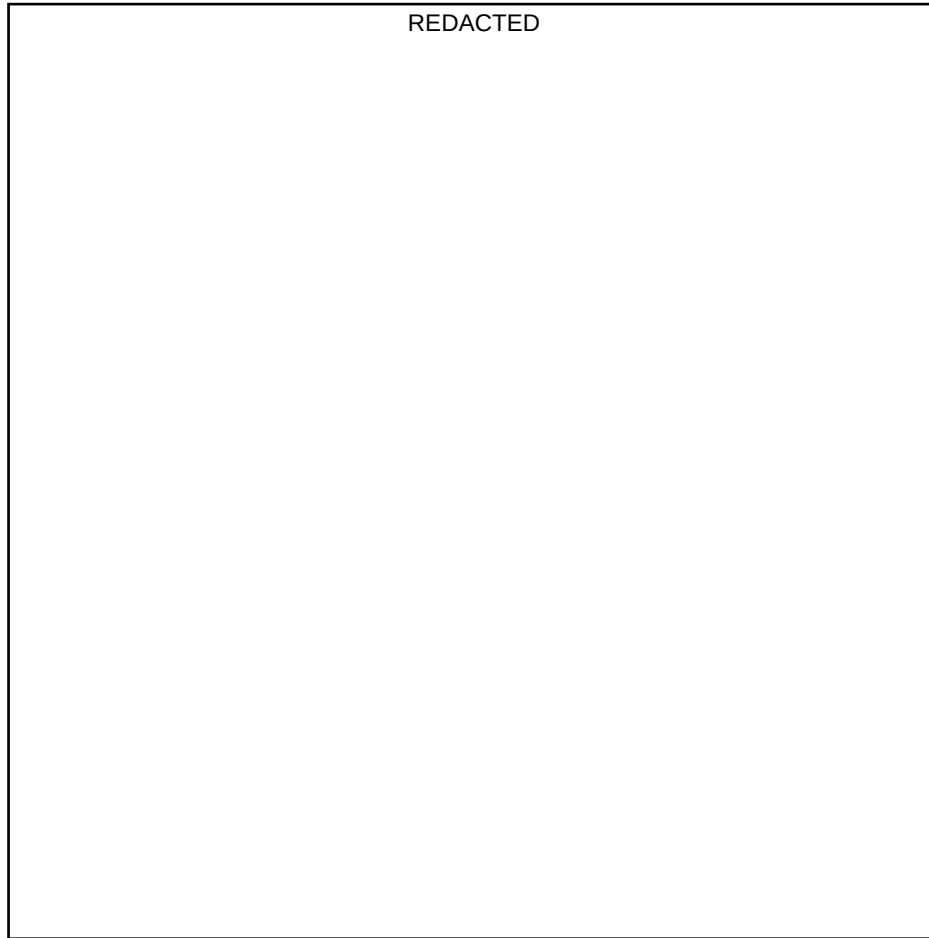


Figure R6. Results of false testing for age-series dust proxies using an R package for Astrochron (Meyers, 2014) with 99%, 95%, and 90% confidence level curves shown.

Spatio-temporal distribution of archaeological record

Q8: In the next stage of the manuscript, the authors compare their dust record with the archaeological and palaeoenvironmental (primarily lake deposits) records of the Arabian Peninsula. In Figure 4c they do this by producing a Kernel Density Estimate (KDE) of dated archaeological and palaeoenvironmental proxies. The KDE has peaks at every ~100 kyr, of decreasing magnitude, although the significance of these peaks is unclear, as there is no background included in this plot. It is likely that the archaeological (and palaeoenvironmental) record decays exponentially with time, as the preservation and discovery potential is so much greater for younger archaeology. Similar trends are found for speleothem preservation, and authors recommend applying exponential backgrounds to KDEs (Scroxton et al., 2016; Weij et al., 2020). It may be the case that in Figure 4c only the largest peak (at ~75ka) is significant.

We appreciate this insightful comment and valuable suggestion, which improves the rigour and

interpretability of our KDE curve analysis. We agree that the decrease in archaeological records with time (driven by reduced preservation and discovery probability for older materials) and lack of a background reference make the significance of the ~100 kyr peaks ambiguous.

The prominent ~75 ka peak in the original KDE curve is due to inclusion of Levantine archaeological age data in the combined dataset, with dense Levantine age clustering during MIS 4 contributing significantly to the ~75 ka peak (Figure R7a), rather than signals solely from the Arabian Peninsula. We re-calculated the KDE curve for Arabian Peninsula-only archaeological ages (excluding Levantine data). The revised Arabian Peninsula-only analysis reveals that the most prominent and statistically significant peak shifts to ~100 ka. This ~100 ka peak is a genuine signal of enhanced Arabian Peninsula archaeological activity, free from the superimposed Levantine MIS 4 signal. The previously observed ~75 ka peak is no longer present in the Arabian-only KDE (Figure R7b).

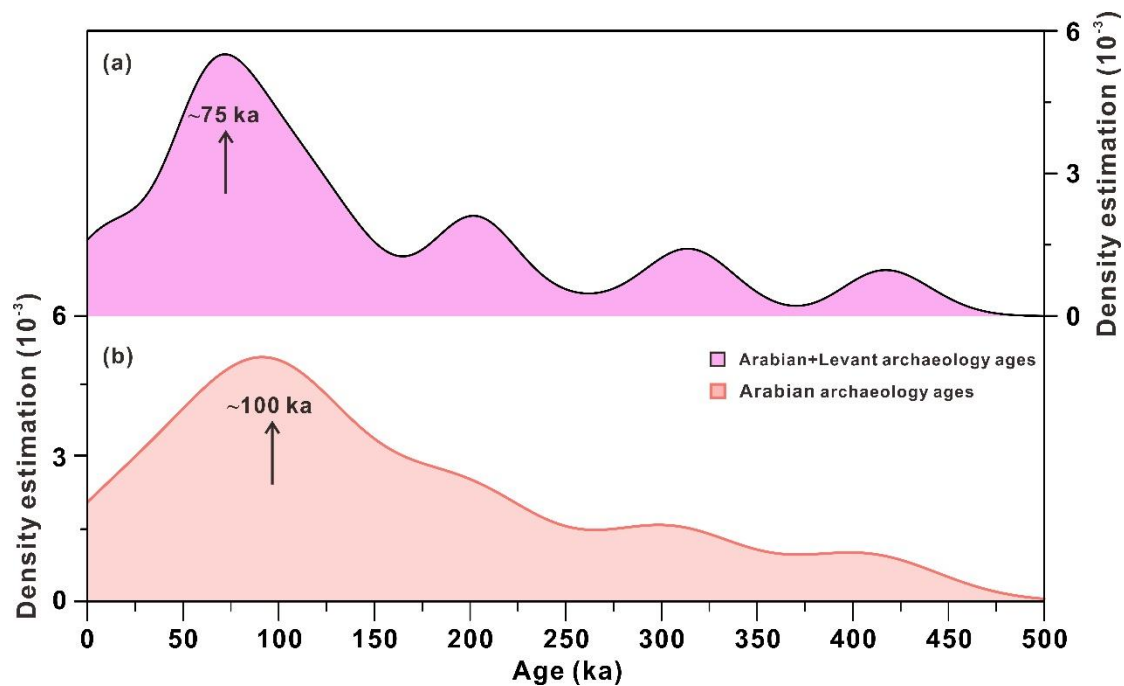


Figure R7. Kernel Density Estimate curves for Arabian and Levantine archaeological ages (a) and only Arabian archaeological ages (b).

Significant ambiguity remains about what frequency distributions of archaeological ages mean with respect to hominin occupation changes. As the reviewer indicates, our KDE curve did not consider exponential climate backgrounds. Previous studies only enable us to learn that Arabian hominin occupation approximates a relationship to monsoon precipitation, which generally increase during wetter periods (Jennings et al., 2015; Nicholson et al., 2020; Rosenberg et al., 2013). But an exponential relationship between archaeological events and known palaeoclimatic records (climatic forcing) is not yet clear in the Arabian Peninsula. Although precipitation variability can be established from continental sediments scattered throughout the Arabian Desert, such records provide only a fragmentary view that becomes scarcer and more difficult to date with increasing age (Breeze et al., 2016; Nicholson et al., 2020; Parton et al., 2018). This limits our ability to overcome problematic generalizations of the Arabian Peninsula palaeoclimate record to address key questions about regional monsoon rainfall continuity, the role of hominin dispersals and occupations into and within the region, and how these dispersals and interactions between populations related to environmental and

ecological changes (Groucutt et al., 2021). Thus, KDE curve construction and interpretation from frequency distributions of Arabian archaeological ages is non-trivial without clear exponential climate backgrounds. After re-evaluation, we decided to replace the KDE curve with a histogram of archaeological ages and a probability density function (PDF) plot from Drake et al. (2013) for statistical analysis of archaeological and palaeoenvironmental proxy ages in the revised Figure 4 (Figure R8). The histogram contains the raw Arabian Peninsula age-frequency distribution (excluding Levantine data) in clear age bins, which avoids ambiguities associated with KDE curve fitting, bandwidth selection, and superposition of exponential decay biases. This revision makes the age clustering characteristics of the proxy record more intuitive and straightforward, with no subjective fitting or smoothing that might obscure the signal. A histogram of Arabian archaeological ages with prominent ~100, 200, 300, and 400 ka peaks (Figure R8) has greater similarities to the probability density of palaeoenvironmental assemblages of dated lacustrine, fluvial, palaeosol, calcrete, and speleothem records as evidence for humidity (Drake et al., 2013). These revisions are incorporated into the revised manuscript and Figure 4d.

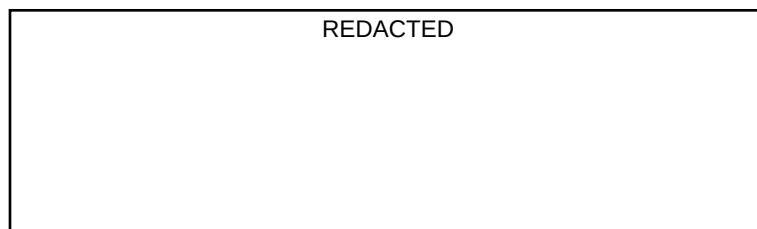


Figure R8. Statistical analysis of Arabian archaeological and fossil hominin age numbers, with probability density function (PDF) curves for the Arabian palaeoenvironmental proxy dataset (Drake et al., 2013).

Q9: *The two dimensional KDE in Figure 4b shows that most of the Arabian Peninsula archaeological sites are from the Levant and are relatively young (<100 ka). In Figure 5 most the Levant is reconstructed as a sub-Mediterranean climate (present day and Eemian) so is not directly relevant to the discussion of desert environments. If the Levantine sites are removed from the dataset, there is not enough evidence from the Arabian Peninsula proper to assign the archaeology to discreet periods of the past.*

We thank the reviewer for this perceptive and constructive comment, which has helped to refine our results, as discussed in our response to Q8. We respond to these concerns as follows.

1) We disaggregated the originally combined archaeological datasets for the Arabian Peninsula and Levant and reprocessed the two-dimensional KDE analysis for each region to generate two independent KDE diagrams (Figure R9b & c). Each is clearly labeled with regional boundaries, age stratification, and density gradients, which resolves the issue of young Levantine archaeological sites (<100 ka) dominating the combined diagram, and makes the characteristics of archaeological remains in each region unambiguous. The revised KDE diagrams reveal a coherent temporal distribution pattern (synchronous frequency) of Arabian Peninsula and Levantine archaeological ages. These hominin occupation phases cluster around ~100, 200, 300, and 400 ka (Figure R9b & c).

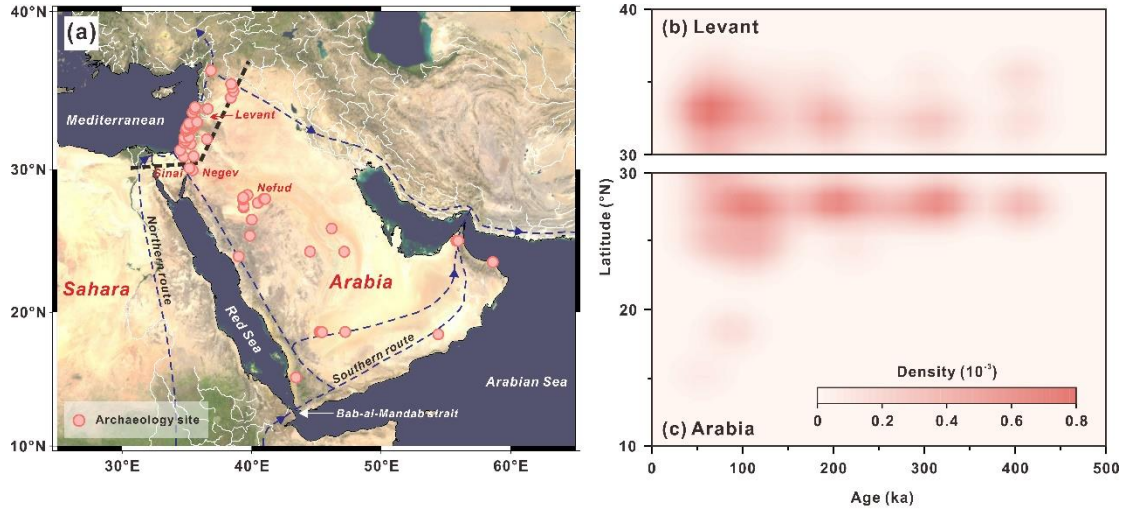


Figure R9. Spatio-temporal distributions of middle-late Pleistocene archaeological records across Arabia. (a) Arabian Peninsula map with middle Pleistocene Arabian and Levantine archaeological sites. Two-dimensional kernel density estimation diagram of spatio-temporal distributions and evolution of archaeological and fossil hominin ages across the Levant (b) and Arabia (c) during the Middle Palaeolithic.

2) To address the problem of an insufficient statistical sample size for Arabian Peninsula archaeological data, which limits identification of discrete human activity periods, we collated published and reliably dated archaeological site data for the Arabian Peninsula (Clark-Wilson et al., 2025; Stimpson et al., 2016; Stewart et al., 2024). An archaeological site may have multiple definite archaeological ages. This data supplementation effectively increases the sample size of the Arabian dataset and improves the statistical robustness of its KDE distribution to provide a more reliable basis for analyzing temporal and spatial human activity patterns in the region. These revisions are incorporated into the revised Figure 4 and Supplementary Information.

Reviewer #2:

This manuscript presents a multi-proxy dust record from the Western Equatorial Indian Ocean, reflecting dust activity and environmental conditions in the arid regions of Arabia. The authors utilize demographic and ecological data to estimate hominin populations in these regions. The correlation between the two datasets leads to the conclusion that significant hominin population expansions occurred mainly during the Green Arabia periods (GAPs). Thus, this study provides the first paleoenvironmental records with orbital resolution for the Arabian arid region, complemented by extensive archaeological findings, and establishes a strong link between climatic changes and hominin expansion and dispersal. Additionally, this study offers a comprehensive understanding of environmental dynamics at orbital timescales. I strongly support the publication of these results in NC; however, the manuscript could benefit from improvements in organization and clarity. I suggest a moderate revision.

We thank Reviewer #2 for their positive feedback. We address their suggestions below. In the revised manuscript, changes are indicated in red lettering.

My main concerns are as follows:

Q1: The structure of the text could be refined. For instance, the paragraph (Lines 60-75) should conclude with the main focus of this study: the linkage between environmental conditions and hominin

dynamics.

Thanks. We have revised this paragraph (Lines 75-79) and reorganized its structure and logic to emphasize the focus of our study for improved readability.

Q2: *In the section titled “Dust Content Changes Over the Past 500 kyr,” it is not effective to present results proxy by proxy.*

We agree and reorganized this section accordingly. The records are discussed according to their environmental implications: dust content variations, glacial-interglacial and GAP-related patterns, source-area weathering intensity (CIA, $\chi_{fd}\%$), aeolian particle size (Zr/Rb), and their links to monsoon dynamics. Proxies are now discussed thematically, rather than one by one. See Lines 118-131.

Q3: *A fundamental assumption of this study is that the core deposits primarily consist of dust input. Evidence supporting this assumption should be summarized in the main text.*

We have moved the summary of evidence supporting the assumption that core deposits are dominated by dust input into the main text (Lines 95-100), as suggested.

Q4: *How was the timescale established?*

Please see our detailed response to Q5 of Reviewer #1. We have added a description and details of age model refinement for core CJ02-08 in the revised manuscript (Lines 88-95) and supplementary information Note 2, respectively.

Q5: *As the authors acknowledge that fluvial terrigenous and biogenic materials also contribute to sediment composition, it should be clarified how these non-aeolian materials affect the changes in Mg/Al and Ti/Ca ratios.*

Thanks. To evaluate rigorously the effect of non-aeolian components and to confirm the aeolian signal in our proxies, we made the following supplementary analysis.

(1) Consistency comparison with established aeolian proxies. In pelagic sediments, hematite and goethite are exclusively detrital (Roberts et al., 2013; Jiang et al., 2022) and are studied widely as dust proxies (Larrasoana et al., 2003; Roberts et al., 2011). We, thus, compare temporal Mg/Al and Ti/Ca trends with hematite and goethite contents across the study interval. All four proxies have synchronous variations with significant positive correlations between Mg/Al, Ti/Ca, and the two aeolian proxies (Figure R10). This consistency indicates that Mg/Al and Ti/Ca changes may reflect aeolian source area hydrological variations rather than fluvial terrigenous and biogenic materials.

(2) Principal Component Analysis (PCA). Although all dust proxies likely respond to aeolian variability, additional processes, sometimes unrelated to atmospheric circulation (e.g. fluvial terrigenous and biogenic alteration), may also influence sediment compositions (Clemens & Prell, 2003). To further limit such biases, we must assess common variance among all four proxies. This can be approached by simple PCA, which indicates that the first component (PC1: i.e., aeolian dust variability) of all of our records ($IRM_{1T@AF80mT}$, I_{Gt} , Mg/Al, and Ti/Ca) explains 79.8% of common variance compared to 12.5% for PC2, which clearly indicates that all four proxies are mainly controlled by the same common forcing, Arabian dust dynamics (Figure R11). Visual comparison of the four records and PC1 and the similar timing of variability indicates a common link to dust content. In summary, our supplementary analyses provide solid evidence to rule out interference of non-aeolian materials, and robustly support our use of Mg/Al and Ti/Ca as aeolian dust proxies. This

analysis is included in Supplementary Information *Note 4 for dust proxies*.

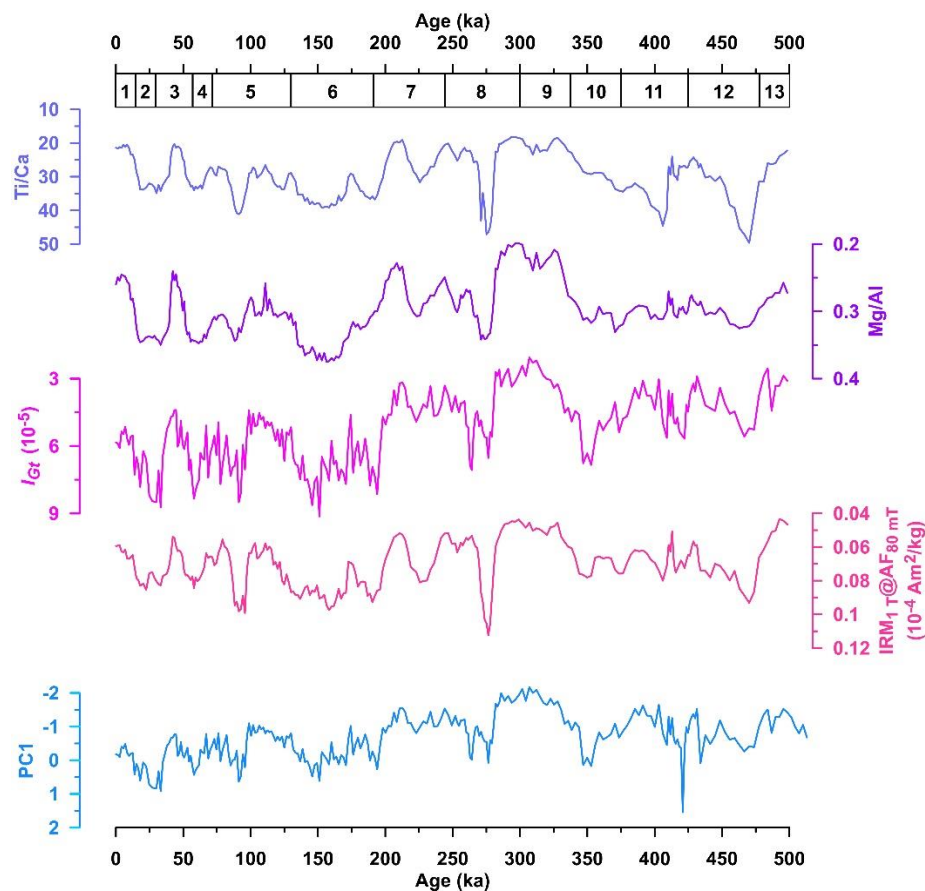


Figure R10. Four dust records and PC1 component variations with age.

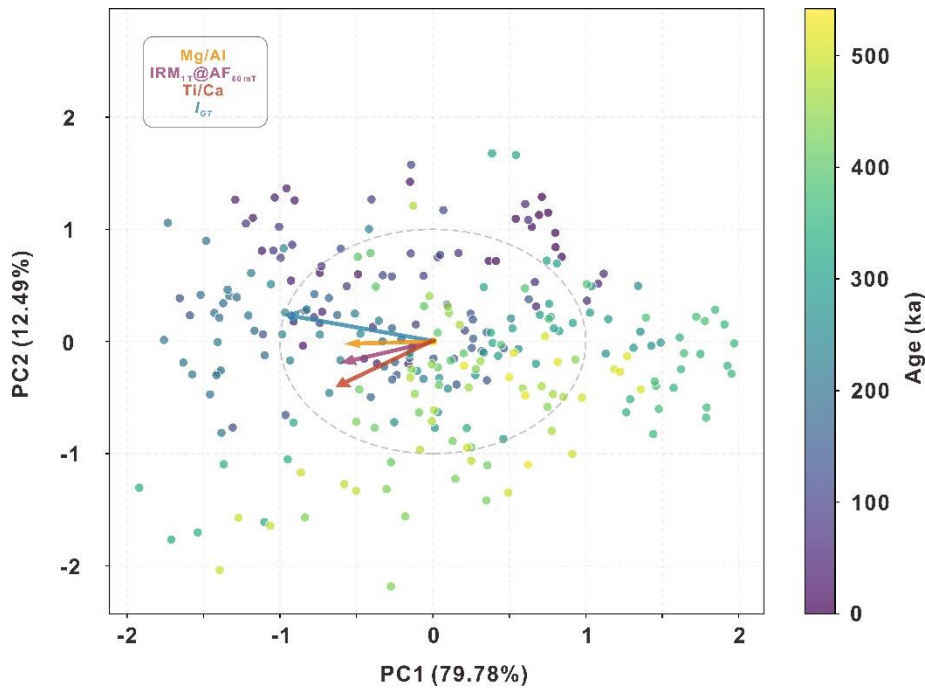


Figure R11. PCA results for our four dust records.

Specific comments:

Q6: Line 61: It would be better to specify the region's name rather than using "in area..."

Thanks. We have revised the statement (Lines 60-61): "Over the past decade, research has documented hominin occupations during GAPs in the Arabian Peninsula that are currently desertified."

Q7: Lines 67-68: Is there evidence supporting the statement that "the debate remains about whether the Arabian Peninsula experienced orbitally-paced GAPs before the late Pleistocene"? It seems that the current climate regime has formed much earlier than the late Pleistocene.

We agree that the current climate regime over the Arabian Peninsula was established well before the late Pleistocene, as supported by long-term southern Arabian speleothem records, which extend back to ~1.1 Ma (Nicholson et al., 2020). Accordingly, we revised the statement (Lines 66-68): "*As a consequence, some degree of uncertainty remains with respect to palaeoclimatic contexts outside of the GAPs and their implications for hominin occupations and dispersals, particularly in the Middle and Late Pleistocene.*"

Q8: Lines 84-89: The logic here may be difficult for general readers to follow. The changes in hematite and goethite should clearly link to dust activity.

Thanks. We added a clearer explanation of why hematite and goethite can serve as reliable dust input proxies in Lines 101-104: "*High-coercivity magnetic minerals, namely hematite and goethite, typically exist as nanoparticles in the interior of the Sahara-Arabian desert (Maher, 2011). In pelagic sediments, hematite and goethite are exclusively detrital (Roberts et al., 2013; Jiang et al., 2022), hence the content of these minerals has been used frequently as dust proxies (Larrasoana et al., 2003; Roberts et al., 2011).*"

Q9: Lines 90-91: Which proxy indicates that these periods were humid?

We clarify the proxy evidence for humid conditions during these intervals (Line 108-110). Lower hematite and goethite contents in pelagic sediments reflect weakened aeolian dust input (consistent with the GAPs noted here) and enhanced source area hydrological activity (Arabian desert), which are direct sedimentary responses to humid conditions.

Q10: Lines 102-112: This paragraph should be moved after the results of all proxies.

Thanks. Done.

Q11: Lines 161-163: When did high dust contents occur?

Higher dust contents were found during glacial periods. Extensive glacial ice sheets increased albedo and cooled the atmosphere to increase the global and Atlantic meridional temperature gradient, which weakened the monsoons. A more southerly and weaker descending sub-tropical westerly jet inhibited convective precipitation (Armstrong et al., 2023), which suppressed precession-induced precipitation change in the Arabian Peninsula. We revised the text to highlight that persistently high dust contents occur during full glacial periods with low orbital eccentricity (Line 174-176).

Q12: Lines 176-182: This paragraph discusses the role of obliquity. I believe the authors go too far with this discussion. If this is the case, please further explain how insolation maxima and obliquity maxima co-drive changes in monsoons.

We agree and further explain it in the revised manuscript (Lines 150-156). We clarify that we attribute appearance of significant eccentricity (~100-kyr) and obliquity (~41-kyr) signals to internal forcing processes, such as global ice volume and greenhouse gas concentrations. The eccentricity signal in our record may reflect ice sheet volume variation (Ruddiman, 2003), while obliquity signals reflect the impact of ice sheet expansion on the subtropical to high latitude insolation gradient (O'Mara et al., 2022). Previous studies clearly demonstrate that ice sheets and greenhouse gases suppress Arabian Peninsula precession-induced precipitation change (Armstrong et al., 2023; Zhou et al., 2024).

Q13: Line 245: 1000%?

Thanks. We replaced “1000%” with “tenfold” in the revised manuscript (Line 265).

Q14: Lines 249-251: Please rephrase the sentence regarding "repeated expansion and contraction during GAPs."

We have revised the sentence to clarify that expansion occurred during GAPs, while contraction occurred subsequent to GAP terminations (Line 270-272).

Q15: Lines 292-305: I do not think this paragraph should revert to addressing dust activity in this section.

Following this suggestion, we moved the paragraph to the section “Controls on Arabian hydroclimatic variability” to support the occurrence of non-primary cycle signals in our Arabian dust record (Lines 198-212).

Q16: Fig. 2g: Please verify the data for $\chi_{fd}\%$.

We re-verified the $\chi_{fd}\%$ data and confirm that an oversight occurred in our calculation: $\chi_{fd}\%$ values were not converted to percentages, which led to an inappropriate expression in Figure 2g. We have now recalculated $\chi_{fd}\%$ data following the standard formula ($\chi_{fd}\% = ((\chi_{lf} - \chi_{hf}) / \chi_{lf}) \times 100\%$) and revised Figure 2g accordingly.

Q17: Fig. 3b: How was the dust index curve generated?

Please see our detailed response to Q2 of Reviewer #1, with revised description on Lines 215-219. More details on the stacked dust index were added to Supplementary Information Note 6.

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Reply to review comments

Reviewer #2 (Remarks to the Author):

I have reviewed the rebuttal letter and the revised manuscript. I am satisfied with the responses and the revisions made. The revision has significantly improved the clarity of the age model and proxy interpretation, as well as the overall structure and readability. The evidence presented provides a solid basis for the environmental interpretation and its influence on hominin occupations and dispersals in the Arabian Peninsula. I am happy to recommend publication of the paper in its current form.

We thank the reviewer for his/her positive feedback. We are happy that all concerns are now addressed.

Reviewer #3 (Remarks to the Author):

The manuscript entitled “Arabian hydroclimate and hominin population dynamics over the last ~500,000 years” offers an interesting insight into the palaeoenvironmental conditions of the Arabian region during the latter half of the Middle Pleistocene. The results are based on data retrieved from a marine core (CJ02-08) in the Indian Ocean, and their interpretation helps refine the development of the 'Green Arabia' periods (GAPs). Furthermore, this palaeoenvironmental information is correlated with the available archaeological record for the same geographical region.

The manuscript's premise is compelling and aligns with recent publications that statistically model human occupation events based on palaeoclimate data. Regarding the processing and interpretation of the palaeoenvironmental data, I see no major issues, the approach appears robust and methodologically sound. However, the correlation between the palaeoenvironmental data and the archaeological record is more problematic.

Thank you for this positive feedback and we are pleased that the reviewer finds our paper to be compelling and robust. With respect to the correspondence between the palaeoenvironment and archaeology, we deal with this issue below.

Q1: *According to the data presented in the main text and supplementary material, most of the archaeological sites do not originate strictly from the Arabian region itself. Instead, they are concentrated along the northern Mediterranean coast, where environmental conditions differed significantly from those in the interior of the Arabian Peninsula.*

As the reviewer noted, Arabia and the Levant represent geographically connected but climatically distinct regions (Engel et al., 2011; Kunkelova et al., 2022; Preston et al., 2015). The Levant lies in the biogeographical zone called the Palaearctic realm which has the typical Mediterranean climate with high precipitation during winter (Bar-Matthews et al., 2003; Rindsberger et al., 1983). By contrast, Arabia lies in the biogeographical zone called the Saharo-Arabian realm, which was repeatedly transformed by summer rainfall from the African monsoon (Fleitmann et al., 2011; Parton et al., 2015; Rosenberg et al., 2013). Accordingly, the CJ02-08 dust record is interpreted as a reconstruction of Arabian hydroclimate rather than that of Levant.

To address the reviewer's concern, we have made some substantial changes to the presentation and organization of the archaeological data.

The Levantine archaeological records were used to provide a wider biogeographic context for hominin connectivity and dispersal between Africa and Eurasia, rather than to use as direct evidence for climatic conditions or population responses within Arabia. We intended to address two related but distinct questions. The first and primary question is how orbital-scale hydroclimatic changes affected environmental suitability and hominin population dynamics within the Arabian Peninsula. The second is whether intervals of increased habitability and landscape connectivity in Arabia coincided with broader phases of hominin movement between Africa and Eurasia, for which the Levant represents a geographically important neighbouring dispersal region. This distinction is particularly important for our interpretation of the northern dispersal route.

We have removed the Levantine archaeological sites from the revised Fig. 3f (**Fig. R1**). This panel is now restricted to archaeological evidence from the Arabian Peninsula and is used specifically to evaluate the relationship between the Arabian hydroclimate record and hominin occupation within Arabia. It avoids the misleading impression that Levantine archaeological record would also respond to the environmental conditions in Arabia.

In the revised Fig. 4a (**Fig. R2a**), archaeological sites from Arabia and the Levant are shown separately and further differentiated according to their cultural-technological attribution. This visual separation makes clear that the sites belong to distinct geographical and climatic regions, while retaining the broader spatial context needed to discuss potential dispersal routes between Africa, Arabia, and Eurasia. The Levantine archaeological dataset has also been added to the revised Fig. 4d (**Fig. R2d**). The revised panel shows the Arabian and Levantine records separately and can be used to explain their different roles in our analysis.

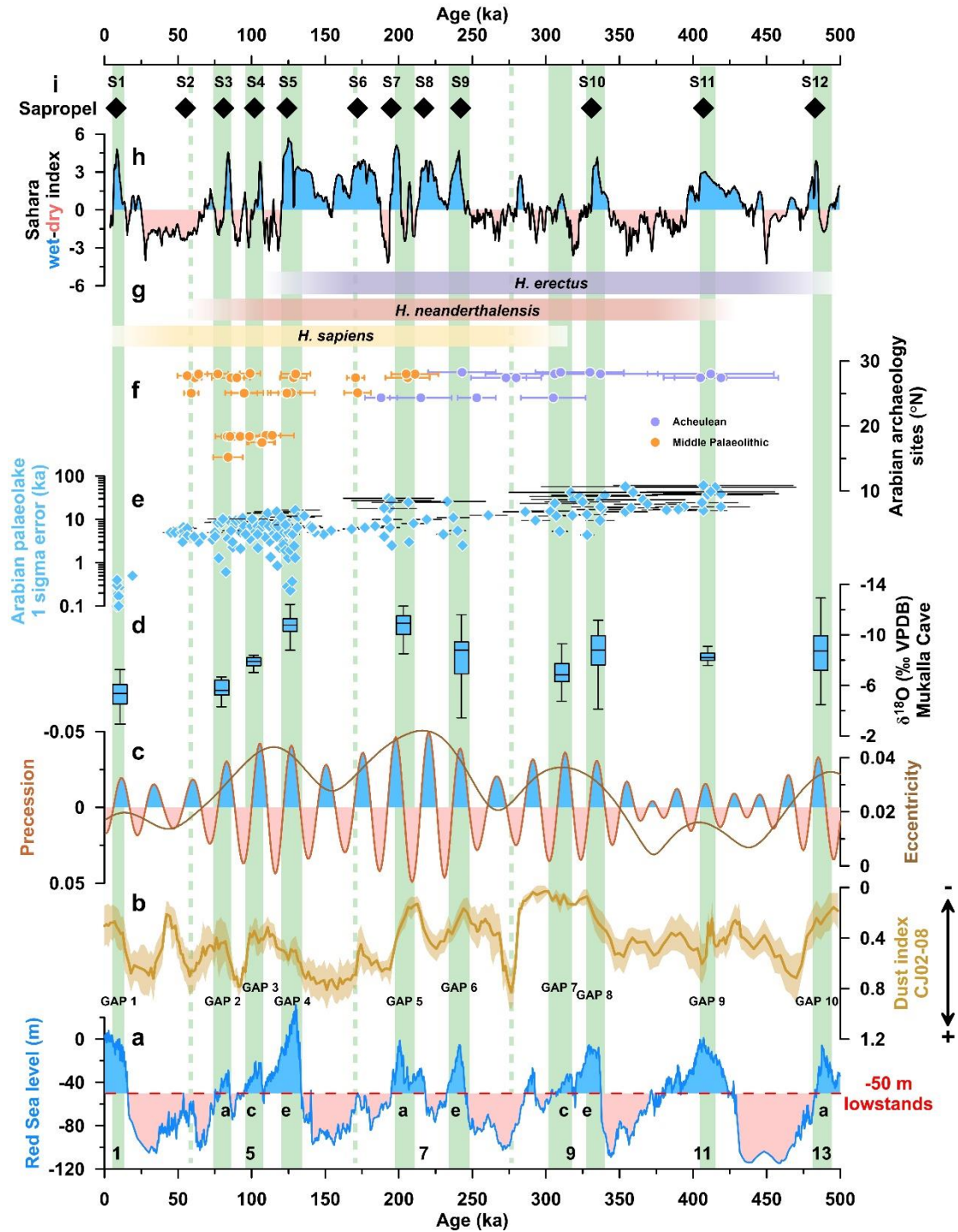


Figure R1 (Fig. 3 in Manuscript). Green Arabia periods (green bars) and palaeoclimate records. (a) Reconstructed Red Sea level variations with the -50 m level marked as an indicator of enhanced conditions for crossing the Bab-al-Mandab Strait (Rohling et al., 2009). (b) Arabian dust index (this study). (c) Eccentricity and precession orbital parameters (Laskar et al., 2004). (d) $\delta^{18}\text{O}$ of Mukalla Cave stalagmites (Nicholson et al., 2020). (e) Northern and Southern Arabian palaeolake ages (Rosenberg et al., 2011; Parton et al., 2015, 2018). (f) Chronology and cultural attribution of hominin occupations in Arabia (e.g., Bretzke et al., 2022, 2025; Groucutt et al., 2015, 2018, 2021; Petraglia et al., 2011). (g) Timing of hominin species evolution (Galway-Witham et al., 2019). (h) Saharan wet-dry index from the Eastern Mediterranean (Grant et al., 2017). (i) Eastern Mediterranean sapropel record (Rohling et al.,

2015). Green dashed lines indicate rapidly increased dust contents within full glacial intervals (~60, 170, and 275 ka).

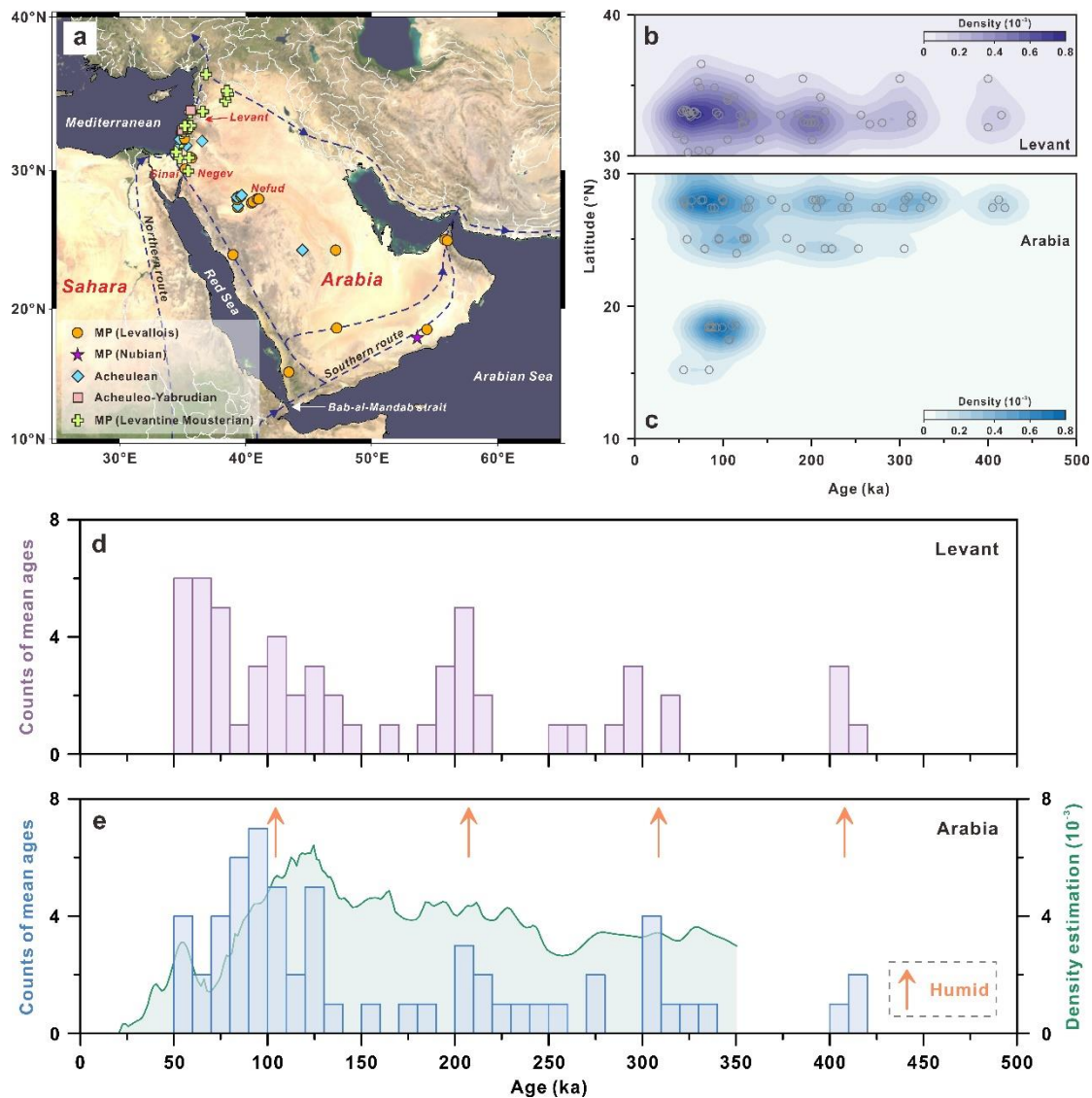


Figure R2 (Fig. 4 in Manuscript). Spatio-temporal distributions of middle-late Pleistocene archaeological records across Arabia and the Levant. (a) Map of Southwest Asia with Arabian and Levantine archaeological sites dating to between 50 and 500 ka (see Supplementary Table S3 and Table S4), with two dispersal routes into Arabia, including the Levantine corridor (northern route) and the narrow Bab-al-Mandab Strait (southern route). MP: Middle Palaeolithic. (b)-(c) Two-dimensional kernel density estimation diagrams of spatio-temporal distributions and evolution of archaeological and fossil hominin mean age estimates across Arabia (bottom) and the Levant (top). (d) Statistical analysis of mean age estimates from Levantine archaeological sites and fossil hominins. (e) Statistical analysis of mean age estimates from Arabian archaeological sites and fossil hominins, with probability density function (PDF) for the Arabian palaeoenvironmental proxy dataset (Drake et al., 2013).

We have reorganized Supplementary Table S3. In the previous paper version, the archaeological data from Arabia and the Levant were summarized without an adequate geographical distinction. We have now divided them into two separate supplementary tables: one containing archaeological records

from the Arabian Peninsula (Supplementary Table S3) and the other containing records from the Levant (Supplementary Table S4). This revision prevents the two datasets from being conflated and enables readers to assess independently the locations, ages, and archaeological contexts of sites from each region.

In addition, we have compared the archaeological evidence from Arabia and the Levant within a biogeographic framework, emphasizing their different roles in reconstructing past human dispersal (Lines 272-290). In the revised *Discussion* section, Levantine archaeological records are no longer treated as direct analogues of Arabian occupation, but are used specifically to evaluate broader biogeographic connectivity between Africa, the Levant, and Arabia. We now clarify that the Levant functioned primarily as a well-watered terrestrial corridor linking northeastern Africa with northern Arabia and Eurasia, while the Arabian records are used to assess hydroclimate-occupation relationships within the peninsula itself.

***Q2:** Furthermore, the archaeological data used have been “anonymized”, in the sense that their cultural attribution is not discussed; that is, Acheulean, Achelo-Yabrudian, and Middle Palaeolithic contexts are analysed in the same manner without any critical distinction. It is worth noting that these technocomplexes were produced by different hominin species, each possessing specific characteristics and behavioural adaptations that have not been taken into account.*

Thanks for your comment. The original version did not provide sufficient information on the cultural attribution of the archaeological records and the possible hominin groups associated with them. As a result, the archaeological dataset may have appeared homogenized, and the relationship between cultural variability, population history, and palaeoenvironmental change was not sufficiently clear.

To improve the description of the archaeological dataset, we added one additional column into the Supplementary Tables S3 and S4 reporting the cultural-technological attribution of each archaeological site. This allows the cultural context of individual records to be evaluated directly and provides a more useful dataset for future culture- or taxon-specific analyses.

Figures are also improved accordingly. In revised Fig. 3f (**Fig. R1f**), Arabian archaeological sites and fossil hominin records are differentiated according to their cultural-technological attribution, including the Acheulean, Middle Palaeolithic Levallois traditions, and the Middle Palaeolithic Nubian Complex. In revised Fig. 4a (**Fig. R2a**), archaeological and fossil records from Arabia and the Levant are distinguished using different symbols for their cultural affiliations. The Levantine records include the Acheulean, Acheulo-Yabrudian, and Middle Palaeolithic Levantine Mousterian, whereas the Arabian records include the Acheulean, Middle Palaeolithic Levallois traditions, and Nubian Complex. These revisions make explicit that the compiled dataset encompasses multiple technological traditions and occupation phases across the two regions, rather than representing a single homogeneous archaeological signal.

The temporal and spatial heterogeneity of different cultural-technological traditions across Arabia and the adjacent Levant are added into the *Discussion* section (Lines 236-261). We now use the observed patterns of technological differentiation and convergence to discuss population structure and biogeographic connectivity across Southwest Asia, and relate these patterns to the timing of GAPS

to assess how humid phases may have periodically reduced ecological barriers across Arabia and facilitated population movement between Africa and Eurasia. The role of the Levant has also been clarified in this framework (Lines 262-290). Rather than treating the Levant as a climatic analogue or culturally homogeneous extension of Arabia, we use the Levantine archaeological record specifically to evaluate the northern biogeographic corridor linking northeastern Africa, the Levant, northern Arabia and Eurasia. Its temporal distribution around GAPS, together with the numbers of archaeological and fossil hominin records along the Levant-northern Arabia axis (**Figure R2**), provides complementary evidence for periods of enhanced regional connectivity.

However, we have not discussed the archaeological taxonomy in detail in the revised main text, which is beyond the principal scope of this study. Here, we focus on hydroclimate, hominin occupation dynamics and biogeographic connectivity. In the revised *Discussion* section, we then use the temporal and spatial variability of the different cultural-technological traditions specifically to evaluate how hydroclimatic conditions changing influence biogeographic connectivity across Southwest Asia.

We recognize that the ~500-kyr interval considered in this study spans multiple hominin species, and that species-specific differences in ecological tolerance, subsistence strategies, mobility and behavior may have resulted in different absolute population densities. Nevertheless, differences in ecological tolerance and adaptive strategies among hominin species, different populations appear to have shared a common tendency to track suitable habitats (Timmermann et al., 2022) (**Fig. R3**) as they shifted across Arabia in response to orbital-scale climate variability (**Fig. R1f**). Accordingly, the model is intended to illustrate the potential magnitude of climate-driven changes in hominin carrying capacity across Arabia, using *Homo sapiens*-based hunter-gatherer analogues as a common reference framework. We have clarified this limitation in the *Discussion* (Line 290-298) and added explanations in both *Method* and *Discussion* that the population estimates are only based on subtropical hunter-gatherer groups and use *Homo sapiens* behaviour as a reference model for other hominin population (Lines 303-306 and 478-479).

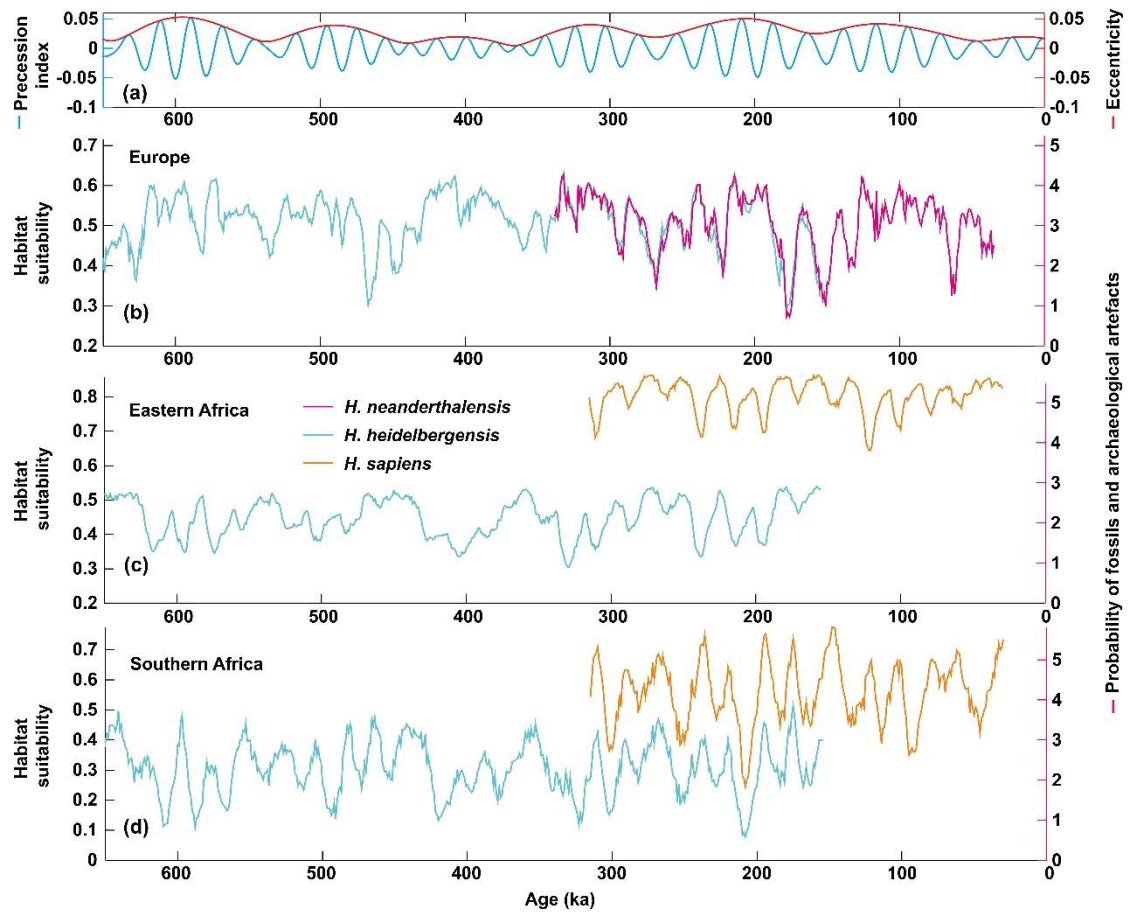


Figure R3 (Fig. S13 in Supplementary Information). (a) Eccentricity (red) and precession (green) orbital parameters (Laskar et al., 2004). (b) Habitat suitability calculated from Timmermann et al. (2022) for *H. heidelbergensis* (green curve) and *H. neanderthalensis* (red curve) in Europe. (c) Same as b but for *H. heidelbergensis* (green) and *H. sapiens* (orange) in eastern-central Africa. (d) Same as c but for southern Africa.

Q3: In many cases, the chronological dates have large margins of error and are utilized without prior critical evaluation. Given this baseline data, while the conclusions presented in the manuscript are supported by the model, they could equally be questioned due to the lack of robustness in the archaeological data.

We thank the reviewer for raising this important issue regarding the reliability of archaeological chronologies and the potential influence of chronological uncertainties on our interpretation. In our revision, we carefully re-evaluated the chronological reliability of the archaeological and fossil hominin datasets. Based on the dating approaches, chronological information on archaeological and fossil hominin records can generally be classified into three categories with different reliabilities.

First, some archaeological materials or fossil hominin remains were dated directly using established numerical dating methods, such as optically stimulated luminescence (OSL), thermoluminescence (TL), electron spin resonance (ESR), Uranium-series dating, and other geochronological techniques. These ages provide the most direct chronological constraints because the dated materials are associated directly with the archaeological or fossil evidence. For these records, we retain the reported ages together with their associated uncertainties. Second, for some archaeological sites and fossil hominin occurrences, the

archaeological materials or fossils have not been directly dated, but the sedimentary layers containing them have been reliably constrained using numerical dating methods. Although these ages do not represent direct measurements of the archaeological materials, they provide robust chronological constraints for occupation layers and generally limit the ages to relatively narrow intervals. We, therefore, retain these records and present them as constrained age ranges based on the reported stratigraphic context and associated chronological framework. Third, some archaeological or fossil hominin ages have been inferred solely from indirect approaches, such as stratigraphic correlation or techno-typological correlation, without independent numerical dating of either the remains/materials or their associated depositional layers. These inferred ages have substantial uncertainties and rely on broader regional correlations. To minimize the potential influence of poorly constrained chronological estimates, we exclude such records from the revised dataset.

Based on this, we revised the chronological information presented in Supplementary Tables S3 and S4. Instead of presenting archaeological ages as single values or simplified age ranges, we now report the original published ages of archaeological layers and fossil hominin, together with the corresponding dating methods. For records with numerical ages and reported uncertainties, we present the ages together with their associated errors. For records where only inferred age ranges are available, we report the estimated chronological intervals and clearly indicate that these ages are based on indirect chronological constraints. This revision allows readers to evaluate the age uncertainty associated with each record.

Importantly, following commonly used approaches for assessing age uncertainty in archaeological studies (Timmermann et al., 2022; Zan et al., 2024), we assessed whether dating uncertainties could substantially influence observed temporal and spatial archaeological patterns. Thus, kernel density distributions were reconstructed using maximum, minimum, and mean age estimates derived from reported dating uncertainties, allowing assessment of whether the overall paleoanthropological pattern is sensitive to chronological uncertainty. The mean age estimate represents the central age reported in the original study, whereas maximum and minimum age estimates represent the oldest and youngest possible ages derived from reported chronological constraints, respectively.

Following this approach, we evaluated the archaeological dataset using alternative age estimates derived from reported uncertainties, including minimum, maximum, and central age estimates. Our analysis indicates that overall temporal archaeological distribution patterns remain consistent among different age scenarios (**Figure R4**), suggesting that the major patterns identified in our study are not artifacts generated by individual age uncertainties. Therefore, although chronological uncertainties exist for individual archaeological sites, they do not substantially alter the apparent fossil hominin and archaeological distribution.

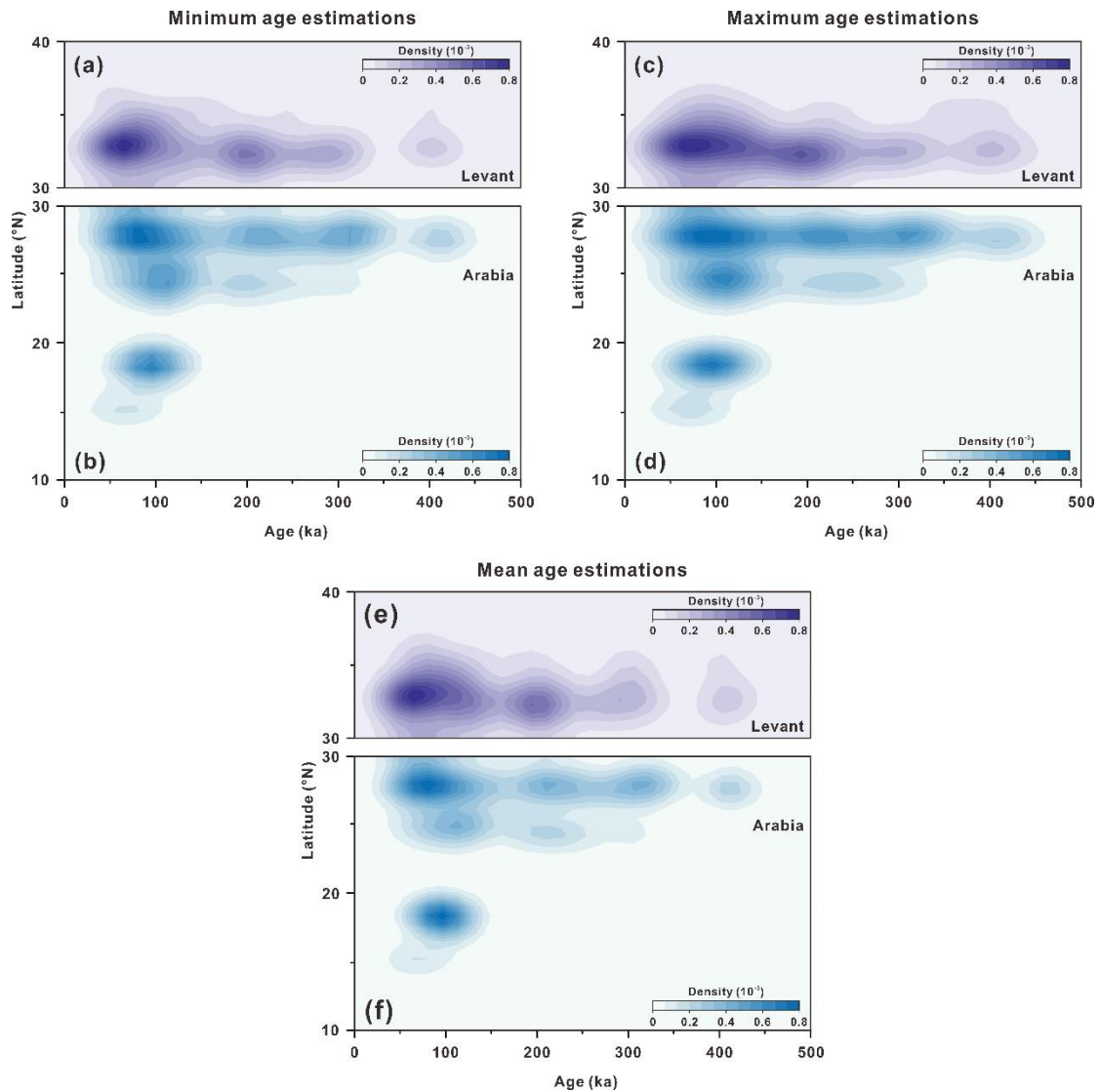


Figure R4 (Fig. S14 in Supplementary Information). Potential influences of dating errors on the spatial and temporal distributions of Middle-Late Pleistocene archaeological and fossil hominin sites across Arabia and the Levant. (a-b) Minimum age estimations. (c-d) Maximum age estimations. (e-f) Mean age estimations.

In the revised manuscript, we added a detailed description in the *Methods* section regarding the compilation and evaluation of archaeological and fossil hominin chronological constraints (Lines 427-472). We now clarify the criteria used to assess chronological reliability, including the distinction between directly dated records, records constrained by reliable dating of associated archaeological layers, and records based only on indirect chronological correlations. We also added an explanation of how age uncertainties were evaluated using different age estimates.

Q4: *Crucially, the conclusions presented are not particularly novel, as they simply suggest that human expansion events correspond to periods of more favourable environmental conditions. Could one expect otherwise?*

We sincerely thank the reviewer for these insightful and valuable suggestions. In the revised version, we highlight the innovations of our study. It has been reported that the Arabian Peninsula was arid during

glacial periods, with hostile environments that obstructed human occupation (Burns et al., 2001; Preusser et al., 2002; Hoffmann et al., 2015). However, available archaeological evidence does not fit well with green Arabia phases on glacial-interglacial timescales. Although the Arabian Palaeolithic record remains limited, hominin presence is still evident during intervals regarded as climatically unfavourable, including glacial stages such as MIS 6 and 4 (Bretzke et al., 2022; Delagnes et al., 2012). With this, these results question the suitability of the glacial-interglacial demographic model and suggest the application of regionally-resolved climatic and ecological data for the contextualisation of archaeological records (a similar conclusion in an African context).

We provide a new regional hydroclimatic perspective on Arabian hominin occupation and dispersal. Rather than documenting the well-established association between hominin occupation and prolonged Green Arabia periods, we resolve short-lived episodes of increased moisture superimposed on otherwise arid glacial conditions at ~275, ~170, and ~60 ka and provide the regional climatic context needed to interpret archaeological evidence from these unfavourable time intervals. Interpretation of these glacial dust peaks is based on the fact that factors other than aridity, such as availability and supply of wind-erodible particles in source areas (Maher et al., 2010; Prospero et al., 2002), can impact marine aeolian flux variations. Although dust source regions are usually arid or hyper arid, the effects of brief but intense precipitation, alluvial/fluvial action, etc., are also important in dust source regions (Prospero et al., 2002). Aeolian dust from the Equatorial Indian Ocean does not only reflect persistent Arabian interior aridity because moisture supply and related physical erosion in the source area are important factors for dust input. Consistent with this interpretation, a dust peak above the 90% confidence level is observed with a 35-kyr frequency in our dust record. The 35-kyr cycle is present in Southern Hemisphere insolation (Clemens & Prell, 1991) and is related closely to latent heat export from the southern subtropical Ocean during glacial intervals, which significantly affects the land-ocean pressure gradient and modulates summer monsoon variability (Clemens & Prell, 1991; Liu et al., 2006). Thus, for these periods, higher aeolian fluxes likely reflect greater terrestrial moisture availability and increased supply of fine wind-erodible particles rather than enhanced source area aridity. Lack of speleothem growth during these periods in southern Arabia suggests that the summer monsoon was too weak to create widespread “green” landscapes here (Nicholson et al., 2020). Relatively small amounts of rainfall were sufficient to activate fine-grained dust, alluvial fans, and to generate fluvial channel flow; but it was insufficient for speleothem growth (Goodall, 1995; Parton et al., 2015; Bretzke et al., 2022). Despite this, the brief wet spells may have played an important role on shaping hominin presence in Arabia. Archaeological records suggest hominin occupation phases at these time intervals.

These brief favourable periods are especially relevant because they coincided with sea-levels of -50 m (below the present level), with a strait passage that was much shallower and narrower than today (Rohling et al., 2009). Emergent shelves may, therefore, have presented an excellent habitat with gentle topography, freshwater availability, and abundant coastal/marine resources (e.g., Parker & Rose 2008; Ghoneim, 2008; Parker & Rose 2008). If emergent shelves were key migration and habitation zones, hominins would have first migrated along or across the Red Sea into Arabia during glacial intervals (Armitage et al., 2011; Delagnes et al., 2012; Petraglia et al., 2010). However, archaeological evidence for such dispersal would now be submerged, making this hypothesis difficult to test directly (Bailey et al., 2007; Rohling et al., 2013). Our dust record provides a more reliable regional hydroclimatic context for understanding how brief rainfall increases during otherwise arid glacial intervals could have

supported hominin occupation and dispersal. We believe that our results may stimulate future underwater archaeological work in the Red Sea, particularly by directing attention to glacial intervals and submerged landscapes with potential to preserve evidence of early hominin dispersal.

We have accordingly refined relevant sections of the manuscript to clarify these points (Lines 189-209 and 337-372). We have refined the regional hydroclimatic context of hominin occupation during short-lived wet episodes within arid glacial intervals, together with potential dispersal routes that may have facilitated such movements, thereby better highlighting the broader significance and novelty of our work.

I believe that before publication can be considered, the archaeological data must be integrated with much greater depth, rather than serving as a mere supplement to the interpretation of palaeoclimate proxy results. A thorough preliminary discussion of the archaeological data, their cultural attribution, and the chronological framework is essential.

We have made targeted revisions throughout the manuscript to address the issues raised above. We hope that these revisions adequately resolve the reviewer's concerns, and we look forward to further feedback.

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Reply to review comments

Reviewer #3 (Remarks to the Author):

The authors have revised and updated the manuscript, successfully addressing several of its main shortcomings. Consequently, I consider that the text is now suitable for publication.

We thank the reviewer for his/her positive feedback. We are happy that all concerns are now addressed.