SCIREA Journal of Geosciences
ISSN: 2995-7206
http://www.scirea.org/journal/Geosciences
April 21, 2026
Volume 10, Issue 1, February 2026
https://doi.org/10.54647/geosciences170375

Aeolioammochronology and the Sand Dunes of the Rub' al Khali (Empty Quarter): A Unique Paleoenvironmental Archive in the Arabian Desert

Ammar Khammash[1], Mahmoud Abbas[1,2]

[1] Khammash architect company, 11181, Amman, Jordan.

[2] Université Paris 1 Panthéon Sorbonne, UMR Archéologie et Sciences de l'Antiquité ArScAn, équipe Archéologies environnementales, Nanterre, France

Email address: khammasham@gmail.com; subariny_m2008@yahoo.com

Abstract:

The sand dunes of the Rub' al Khali (Empty Quarter) preserve a key archive of environmental change in Arabia, a critical region along routes of human dispersal out of Africa. This mini-review evaluates the principal dating techniques applied to constrain the timing of dune formation, including optically stimulated luminescence (OSL), radiocarbon dating of interdune deposits, and U–Th dating of regional archives. We also discuss an emerging chronological framework—aeolioammochronology—as an innovative approach for dating aeolian sand bodies. Integrating multiple dating methods enables the construction of more robust chronologies of sediment deposition and landscape evolution across the dune field, while reducing uncertainties inherent to single techniques. Establishing precise timelines for phases of dune accumulation and stabilization is essential for linking desert dynamics to glacial–interglacial climate cycles and for assessing when Arabia functioned as either a barrier or corridor for *Homo sapiens* dispersing into Eurasia.

Keywords:

Rub' al Khali, aeolioammochronology, paleoenvironmental reconstruction, hyper-arid regions, Arabia.

Main text

Sand dunes form through the interaction of wind (or, less commonly, water flow), sediment supply, and surface conditions, governed by well-established physical processes of sediment transport and deposition (McKenna Neuman, 1993; Stide, 2012; Vriend and Bacik, 2025). When wind velocity exceeds the threshold needed to mobilize sand grains, particles move primarily by saltation (short hopping motions), with finer grains entering suspension and coarser grains creeping along the surface (Baas, 2019; Merrison, 2012). As wind encounters an obstacle or a decrease in velocity, its capacity to carry sediment drops, causing sand to accumulate and initiate dune growth. Continued transport drives sand up the gentle windward slope, while gravity-driven avalanching on the steeper leeward slip face maintains a characteristic dune profile near the angle of repose (~30–34°) (Condie and Sherwood, 2006; Iversen and Rasmussen, 1999; Roback, 2021). Variations in wind regime, sand availability, and vegetation or moisture control dune morphology, producing forms such as barchan, transverse, linear, and star dunes (Almasrahy and Mountney, 2013, 2014; Amiha et al., 2025). Over time, dunes migrate in the dominant wind direction while preserving their shape, making them dynamic indicators of environmental conditions in arid, coastal, and even extraterrestrial landscapes (Baas and Delobel, 2022; Nield and Baas, 2008).

The Rub' al Khali, or Empty Quarter, is the world's largest contiguous sand desert, covering approximately 650,000 square kilometers across Saudi Arabia, Oman, the UAE, and Yemen (Fig.1). This vast desert presents a unique opportunity to investigate past climatic and environmental conditions due to its extensive and relatively undisturbed sand dune formations (Almasrahy and Mountney, 2013, 2014). Unlike other paleoenvironmental archives such as lake sediments, speleothems, coral reefs, and marine deposits, the sand dunes, particularly from Rub’ al Khali, offer exceptional spatial coverage, continuity, and preservation, during the Quaternary period (Glennie, 2020; Leighton et al., 2013). These characteristics make it an unparalleled resource for understanding long-term environmental dynamics in hyper-arid regions.

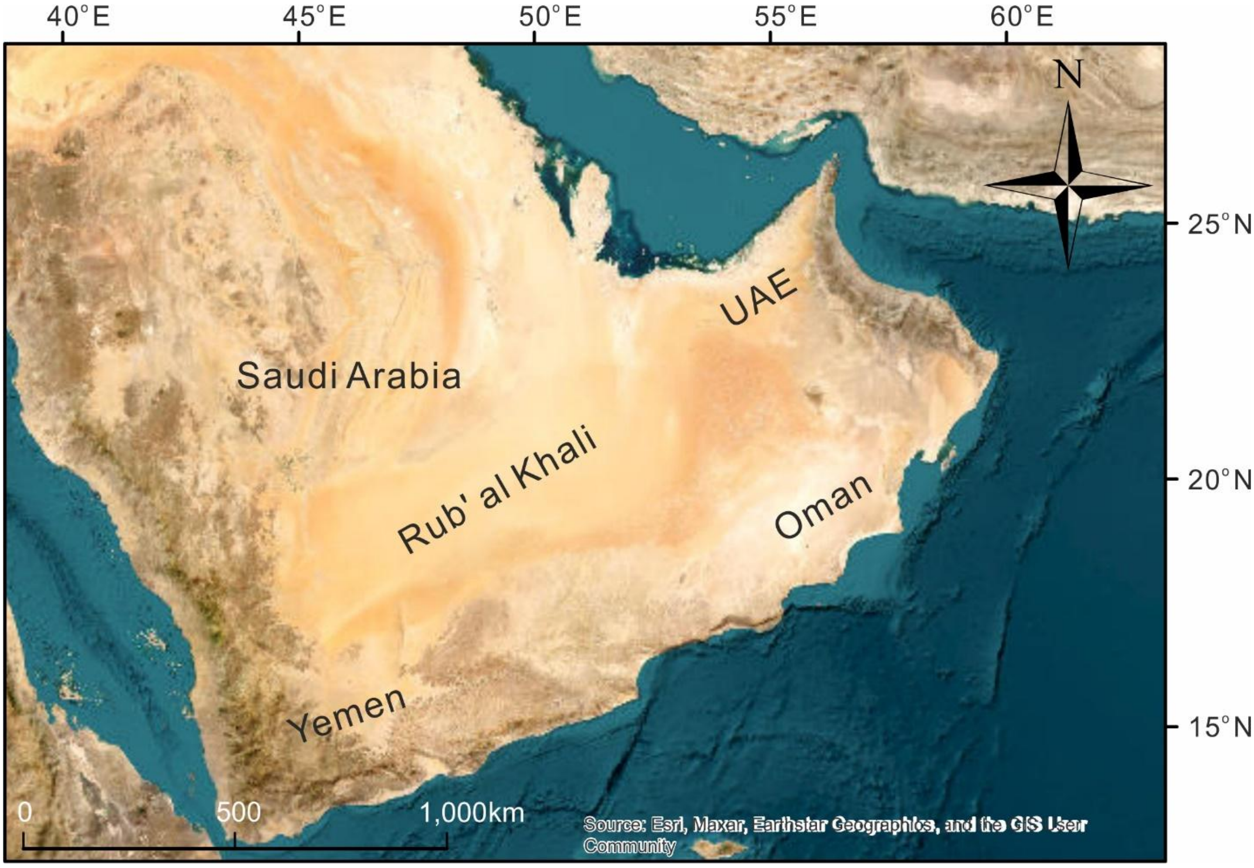

Fig.1 Location map of the southern part of the Arabian Peninsula showing the Rub’ al Khali desert.

The Rub’a al Khali desert is located along a very important corridor for human dispersals out of Africa during Late Pleistocene (Abbas et al., 2023; Armitage et al., 2011; Groucutt et al., 2015b, Groucutt et al., 2018; Rosenberg et al., 2013). Therefore, establishing a robust chronology for the sand dunes of the Rub' al Khali (Empty Quarter) is essential for reconstructing past hydroclimatic variability across Arabia and assessing windows of human habitability (Leighton et al., 2013; Mason et al., 2009; Qi et al., 2023). Constraining the timing of these phases therefore provides a framework for understanding desert expansion, landscape connectivity and potential dispersal corridors during the Late Pleistocene and Holocene (Abbas et al., 2023; Abbas et al., 2026; Al-Saqarat et al., 2021; Armitage et al., 2011; Groucutt et al., 2018; Groucutt et al., 2015a; Groucutt et al., 2015b). The principal dating method applied to dunes in the Rubʿ al Khali and wider Arabia is optically stimulated luminescence (OSL), which determines the time since quartz grains were last exposed to sunlight (e.g., Atkinson et al., 2012; Farrant et al., 2015). In addition, radiocarbon dating of interdune organic deposits and palaeolake sediments, and regional U–Th dating of speleothems, have been used to complement luminescence chronologies and refine palaeoclimatic interpretations in southern Arabia (e.g., Fleitmann et al., 2003; Rosenberg et al., 2011; Rosenberg et al., 2013).

Despite important progress, the chronological framework of the Rub' al Khali remains subject to several limitations. While OSL dating well suited to dating aeolian sands, can be affected by incomplete bleaching, post-depositional mixing and dose-rate uncertainties in highly mobile dune systems (Gliganic et al., 2016; Leighton et al., 2014; Thomas and Burrough, 2016). Radiocarbon dating is restricted to the relatively short time range of preserved organic material and is often limited in hyper-arid environments where such material is scarce (Derbyshire and Singhvi, 2026; Hajdas et al., 2021). U–Th ages from speleothems provide valuable regional climate context, but they are typically obtained outside the dune fields themselves and may not directly reflect local sediment dynamics (McDermott, 2004; Richards and Dorale, 2003). These constraints highlight the need to integrate dune chronologies with independently dated regional records and to explicitly link phases of dune accumulation and stabilization to broader glacial–interglacial cycles, enabling a more coherent understanding of how global climate forcing shaped Arabian desert landscapes.

Aeolioammochronology represents an emerging and innovative approach to establishing robust chronologies for aeolian sand bodies, particularly in large desert systems where traditional dating methods face significant limitations. The term combines elements from Greek words: 'aeolian' (relating to wind-blown processes), 'ammos' (sand), and 'chronos' (time), reflecting the method's focus on reconstructing the temporal sequence of wind-deposited sand layers. A stratigraphically integrated, multi-proxy chronological framework for aeolian sedimentary systems that combines internal dune architecture, independent geochronological markers, and regional paleoclimate correlation to reconstruct temporally coherent depositional histories. The method builds on the premise that sand dunes, much like other layered natural archives, preserve stratigraphic sequences that reflect successive phases of deposition, stabilization and environmental change. By carefully analysing internal dune stratification, mineralogical composition, interbedded volcanic ash layers, and associated paleoecological indicators such as pollen, aeolioammochronology seeks to construct a more integrated and internally consistent timeline of dune formation. In doing so, it moves beyond reliance on a single numerical age and instead treats dunes as complex sedimentary archives that can be read in a multi-proxy framework.

Traditional dating of desert dunes has relied predominantly on OSL, which determines the time elapsed since quartz or feldspar grains were last exposed to sunlight (Aitken, 1998). OSL has revolutionized Quaternary desert research and remains a cornerstone technique for dating aeolian deposits (Farrant et al., 2015). However, in large and dynamic dune fields, such as the Rub' al Khali, OSL ages can be complicated by several factors (Atkinson et al., 2012; Leighton et al., 2014). Partial bleaching of sand grains prior to burial may lead to age overestimation, while sediment reworking, bioturbation, or post-depositional mixing can introduce age scatter within stratigraphically complex sequences (Duller, 2008). Dose-rate heterogeneity in thick dune bodies can further increase uncertainty (Costas et al., 2012; Heydari and Guérin, 2018). Although statistical models such as the Minimum Age Model have been developed to address some of these issues, they do not fully resolve the structural complexity of dune stratigraphy (e.g; Sherman, 1995).

Aeolioammochronology addresses these limitations by explicitly integrating sedimentological architecture with independent chronological markers. Internal layering patterns within dunes—such as cross-bedding sets, bounding surfaces, palaeosols, and interdune horizons—record shifts in wind regime, sediment supply, and moisture availability. When these layers are analysed in combination with mineral composition and grain-source signatures, they can reveal changes in provenance linked to regional climatic fluctuations. The incorporation of volcanic ash layers (tephra), where present, provides time-parallel marker horizons that can be independently dated using established geochronological techniques. Similarly, pollen assemblages preserved in interdune or stabilized surfaces can be correlated with broader paleoenvironmental frameworks. Together, these proxies allow for cross-validation of ages and for identifying depositional phases that correspond to well-known climatic transitions.

The conceptual foundation of aeolioammochronology parallels that of ice core chronology. In polar regions, layered ice deposits provide annually or seasonally resolved records of past atmospheric conditions (Delmas, 1994; Hvidberg et al., 2012). Each layer represents a discrete interval of deposition, and through stratigraphic continuity, a long-term climatic record can be reconstructed (Boutron, 1995; Cutts, 1973). Aeolioammochronology applies a comparable principle to wind-deposited sand layers in arid landscapes. While dune laminae are not annual in the strict sense, their vertical stacking reflects discrete depositional events and environmental states. By analysing these sequences systematically and anchoring them to independent chronological controls, it becomes possible to reconstruct a high-resolution history of dune growth, stabilization, and reactivation.

The need to apply aeolioammochronology is particularly compelling in the Rub' al Khali, one of the largest continuous sand deserts on Earth. The dune records of this region capture multiple climatic periods spanning the Late Pleistocene and Holocene, including phases of intensified aridity and intervals of enhanced monsoon influence. Yet despite decades of research, the chronological framework of the Rub' al Khali remains uneven and spatially fragmented (Almasrahy and Mountney, 2013, 2014; Atkinson et al., 2012; Leighton et al., 2013; Leighton et al., 2014). Many existing age determinations are based on isolated OSL samples, often without detailed stratigraphic integration (e.g; Atkinson et al., 2012; Leighton et al., 2013). As a result, correlating dune-building phases with regional glacial–interglacial cycles or abrupt climatic events remains challenging.

A multi-dating strategy grounded in aeolioammochronology would enable more robust temporal correlations between dune dynamics and global climate forcing. By linking internal dune stratigraphy to independently dated tephra layers, paleoecological indicators, and regional archives such as speleothems or marine cores, researchers can reduce chronological ambiguity and identify synchronous events across broader geographic scales. This integrated approach is essential for determining whether major dune accumulation phases correspond to Marine Isotope Stage boundaries, monsoon weakening events, or rapid cooling intervals.

Beyond paleoclimate reconstruction, improving the chronology of the Rub' al Khali has significant implications for understanding human dispersals out of Africa (Abbas et al., 2023; Abbas et al., 2026; Groucutt et al., 2018; Groucutt et al., 2015a; Groucutt et al., 2015b). Arabia occupies a strategic position at the crossroads of Africa, the Middle East and Eurasia (Groucutt et al., 2018; Groucutt et al., 2015a; Groucutt et al., 2015b). Periods of dune stabilization and increased moisture would have enhanced landscape connectivity, creating habitable corridors for *Homo sapiens* expansion (Armitage et al., 2011; Rosenberg et al., 2011; Rosenberg et al., 2013). Conversely, phases of intensified dune accumulation and hyper-aridity may have acted as barriers to movement (Goudie et al., 1987; Preusser et al., 2005). Without precise and regionally coherent chronologies, it is difficult to evaluate the timing and environmental context of these dispersal windows.

Dunes of the Rubʿ al Khali represent a major archive of Quaternary environmental change, but robust interpretation requires chronologies that combine numerical dating with explicit stratigraphic context. OSL remains the cornerstone method for aeolian sands, while radiocarbon and U–Th chronologies provide complementary constraints and regional climate context. A stratigraphy-first, multi-proxy approach (aeolioammochronology) offers a pathway to more internally consistent dune age models, improved regional correlations, and stronger tests of how Arabian deserts responded to glacial–interglacial forcing and shaped potential dispersal corridors.

By integrating multiple dating techniques within the framework of aeolioammochronology, researchers can construct a more reliable timeline of environmental change and landscape evolution in the Rub' al Khali. This approach not only addresses the methodological shortcomings of single-technique dating but also positions the dune field as a central archive for regional and global paleoclimatic studies. Ultimately, applying aeolioammochronology in this vast desert system offers the potential to transform our understanding of Arabian environmental history and its role in shaping both climate dynamics and human journeys across continents.

References

[1] Abbas, M., Lai, Z., Jansen, J.D., Tu, H., Alqudah, M., Xu, X., Al-Saqarat, B.S., Al Hseinat, M.a., Ou, X., Petraglia, M.D., Carling, P.A, 2023. Human dispersals out of Africa via the Levant. *Science Advances* 9, eadi6838.

[2] Abbas, M., Lai, Z., Tu, H., Ou, X., Carling, P.A., Lin, P., Alqudah, M., Al-Saqarat, B.S., Qiu, T., Petraglia, M.D., Rezek, Z., Jansen, J.D., 2026. A stable environmental niche for humans in the southern Levant 70–40 ka. *Quaternary Science Reviews* 377, 109855.

[3] Aitken, M.J., 1998. *Introduction to optical dating*: the dating of Quaternary sediments by the use of photon-stimulated luminescence. Clarendon Press.

[4] Al-Saqarat, B.S., Abbas, M., Lai, Z., Gong, S., Alkuisi, M.M., Hamad, A.M.A., Carling, P.A., Jansen, J.D., 2021. A wetland oasis at Wadi Gharandal spanning 125–70 ka on the human migration trail in southern Jordan. *Quaternary Research* 100, 154-169.

[5] Almasrahy, M.A., Mountney, N.P., 2013. Spatial variability in eolian dune and interdune morphology in the Rub'Al-Khali dunefield, Saudi Arabia. *AAPG Search and Discovery*.

[6] Almasrahy, M.A., Mountney, N.P., 2014. Approaches to modelling stratigraphic heterogeneity in mixed fluvial and aeolian hydrocarbon reservoirs. *AAPG Search and Discovery* 90189, 1-4.

[7] Amiha, R., Kabbachi, B., Ait Haddou, M., Quesada-Román, A., Bouchriti, Y., Abioui, M., 2025. Morphodynamics, Genesis, and Anthropogenically Modulated Evolution of the Elfeija Continental Dune Field, Arid Southeastern Morocco. *Earth* 6, 100.

[8] Armitage, S.J., Jasim, S.A., Marks, A.E., Parker, A.G., Usik, V.I., Uerpmann, H.-P., 2011. The southern route “out of Africa”: evidence for an early expansion of modern humans into Arabia. *Science* 331, 453-456.

[9] Atkinson, O.A.C., Thomas, D.S.G., Goudie, A.S., Parker, A.G., 2012. Holocene development of multiple dune generations in the northeast Rub’al-Khali, United Arab Emirates. *The Holocene* 22, 179-189.

[10] Baas, A.C.W., 2019. Grains in motion. *Aeolian Geomorphology*: A New Introduction, 27-60.

[11] Baas, A.C.W., Delobel, L.A., 2022. Desert dunes transformed by end-of-century changes in wind climate. *Nature Climate Change* 12, 999-1006.

[12] Boutron, C.F., 1995. Historical reconstruction of the earth's past atmospheric environment from Greenland and Antarctic snow and ice cores. *Environmental Reviews* 3, 1-28.

[13] Condie, S.A., Sherwood, C.R., 2006. Sediment distribution and transport across the continental shelf and slope under idealized wind forcing. *Progress in Oceanography* 70, 255-270.

[14] Costas, I., Reimann, T., Tsukamoto, S., Ludwig, J., Lindhorst, S., Frechen, M., Hass, H.C., Betzler, C., 2012. Comparison of OSL ages from young dune sediments with a high-resolution independent age model. *Quaternary geochronology* 10, 16-23.

[15] Cutts, J.A., 1973. Nature and origin of layered deposits of the Martian polar regions. *Journal of Geophysical Research* 78, 4231-4249.

[16] Delmas, R.J., 1994. Ice records of the past environment. *Science of the total environment* 143, 17-30.

[17] Derbyshire, E., Singhvi, A.K., 2026. Paleoenvironmental reconstruction in arid lands. *CRC Press*.

[18] Duller, G.A.T., 2008. *Luminescence Dating: guidelines on using luminescence dating in archaeology*.

[19] Farrant, A.R., Duller, G.A.T., Parker, A.G., Roberts, H.M., Parton, A., Knox, R.W.O., Bide, T., 2015. Developing a framework of Quaternary dune accumulation in the northern Rub'al-Khali, Arabia. *Quaternary International* 382, 132-144.

[20] Fleitmann, D., Burns, S.J., Mudelsee, M., Neff, U., Kramers, J., Mangini, A., Matter, A., 2003. Holocene forcing of the Indian monsoon recorded in a stalagmite from southern Oman. *Science* 300, 1737-1739.

[21] Glennie, K.W., 2020. The desert of southeast Arabia: a product of Quaternary climatic change, Quaternary deserts and climatic change. *CRC Press*, pp. 279-291.

[22] Gliganic, L.A., Cohen, T.J., Slack, M., Feathers, J.K., 2016. Sediment mixing in aeolian sandsheets identified and quantified using single-grain optically stimulated luminescence. *Quaternary Geochronology* 32, 53-66.

[23] Goudie, A.S., Warren, A., Jones, D.K.C., Cooke, R.U., 1987. The Character and Possible Origins of the Aeolian Sediments of the Wahiba Sand Sea, Oman. *The Geographical Journal* 153, 231-256.

[24] Groucutt, H.S., Grün, R., Zalmout, I.A., Drake, N.A., Armitage, S.J., Candy, I., Clark-Wilson, R., Louys, J., Breeze, P.S., Duval, M., 2018. Homo sapiens in Arabia by 85,000 years ago. *Nature ecology & evolution* 2, 800-809.

[25] Groucutt, H.S., Petraglia, M.D., Bailey, G., Scerri, E.M., Parton, A., Clark-Balzan, L., Jennings, R.P., Lewis, L., Blinkhorn, J., Drake, N.A., 2015a. Rethinking the dispersal of Homo sapiens out of Africa. *Evolutionary Anthropology: Issues, News, and Reviews* 24, 149-164.

[26] Groucutt, H.S., White, T.S., Clark-Balzan, L., Parton, A., Crassard, R., Shipton, C., Jennings, R.P., Parker, A.G., Breeze, P.S., Scerri, E.M., 2015b. Human occupation of the Arabian empty quarter during MIS 5: evidence from Mundafan Al-Buhayrah, Saudi Arabia. *Quaternary Science Reviews* 119, 116-135.

[27] Hajdas, I., Ascough, P., Garnett, M.H., Fallon, S.J., Pearson, C.L., Quarta, G., Spalding, K.L., Yamaguchi, H., Yoneda, M., 2021. Radiocarbon dating. *Nature Reviews Methods Primers* 1, 62.

[28] Heydari, M., Guérin, G., 2018. OSL signal saturation and dose rate variability: Investigating the behaviour of different statistical models. *Radiation Measurements* 120, 96-103.

[29] Hvidberg, C.S., Fishbaugh, K.E., Winstrup, M., Svensson, A., Byrne, S., Herkenhoff, K.E., 2012. Reading the climate record of the Martian polar layered deposits. *Icarus* 221, 405-419.

[30] Iversen, J.D., Rasmussen, K.R., 1999. The effect of wind speed and bed slope on sand transport. *Sedimentology* 46, 723-731.

[31] Leighton, C.L., Bailey, R.M., Thomas, D.S.G., 2013. The utility of desert sand dunes as Quaternary chronostratigraphic archives: evidence from the northeast Rub'al Khali. *Quaternary Science Reviews* 78, 303-318.

[32] Leighton, C.L., Thomas, D.S.G., Bailey, R.M., 2014. Reproducibility and utility of dune luminescence chronologies. *Earth-Science Reviews* 129, 24-39.

[33] Mason, J.A., Lu, H., Zhou, Y., Miao, X., Swinehart, J.B., Liu, Z., Goble, R.J., Yi, S., 2009. Dune mobility and aridity at the desert margin of northern China at a time of peak monsoon strength. *Geology* 37, 947-950.

[34] McDermott, F., 2004. Palaeo-climate reconstruction from stable isotope variations in speleothems: a review. *Quaternary Science Reviews* 23, 901-918.

[35] McKenna Neuman, C., 1993. A review of aeolian transport processes in cold environments. *Progress in physical Geography* 17, 137-155.

[36] Merrison, J.P., 2012. Sand transport, erosion and granular electrification. *Aeolian Research* 4, 1-16.

[37] Nield, J.M., Baas, A.C.W., 2008. The influence of different environmental and climatic conditions on vegetated aeolian dune landscape development and response. *Global and Planetary Change* 64, 76-92.

[38] Preusser, F., Radies, D., Driehorst, F., Matter, A., 2005. Late Quaternary history of the coastal Wahiba Sands, Sultanate of Oman. *Journal of Quaternary Science* 20, 395-405.

[39] Qi, L., Gaur, M.K., Squires, V.R., 2023. Sand Dunes of the Northern Hemisphere.

[40] Richards, D.A., Dorale, J.A., 2003. Uranium-series chronology and environmental applications of speleothems. *Reviews in Mineralogy and Geochemistry* 52, 407-460.

[41] Roback, K.P., 2021. Investigating sand transport and landslides, and implications for past and present environments on Mars and Earth. *California Institute of Technology*.

[42] Rosenberg, T., Preusser, F., Fleitmann, D., Schwalb, A., Penkman, K., Schmid, T., Al-Shanti, M., Kadi, K., Matter, A., 2011. Humid periods in southern Arabia: windows of opportunity for modern human dispersal. *Geology* 39, 1115-1118.

[43] Rosenberg, T.M., Preusser, F., Risberg, J., Plikk, A., Kadi, K.A., Matter, A., Fleitmann, D., 2013. Middle and Late Pleistocene humid periods recorded in palaeolake deposits of the Nafud desert, Saudi Arabia. *Quaternary Science Reviews* 70, 109-123.

[44] Sherman, D.J., 1995. Problems of scale in the modeling and interpretation of coastal dunes. *Marine Geology* 124, 339-349.

[45] Stide, A.H., 2012. Offshore tidal sands: processes and deposits. *Springer Science & Business Media*.

[46] Thomas, D.S.G., Burrough, S.L., 2016. Luminescence-based dune chronologies in southern Africa: Analysis and interpretation of dune database records across the subcontinent. *Quaternary International* 410, 30-45.

[47] Vriend, N.M., Bacik, K.A., 2025. The Dynamics of Sand Dunes. *Annual Review of Fluid Mechanics* 58.