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Dakhla Sand Dunes in Southern Morocco: Using Grain Size Analysis to Understand Wind Dynamics

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Abstract

Morocco is affected by desertification in its southern and southeastern territories. A visible manifestation of desertification in southern Morocco is the movement of dune sands shaped by wind dynamics. This paper investigates the characteristics and distribution of sand in the study area using granulometric analysis to determine physical properties and textural parameters such as mean grain size, sorting, skewness, and kurtosis. To better understand the dynamics of sandy deposit emplacement in the Dakhla region, a dynamic and sedimentological study was conducted. This study constituted the second phase of the research and involved laboratory analyses, particularly granulometric measurements, to determine grain-size distributions.

Sand samples were collected from various locations across the region extending from the bay through the Dakhla area to the Awserd region. Aeolian dynamics responsible for the formation of Dakhla dunes produced sand stocks composed of one or more grain-size fractions, with modes at 113–143 µm, 225–283 µm, and 358–450 µm. Most of the analyzed samples exhibited bimodal distributions, with clearly distinguishable modes corresponding to mixtures of two homogeneous particle-size populations.

Three distinct particle-size distributions characterize these sand deposits. The first is a minor unimodal distribution of well-sorted medium grains, reflecting an aeolian evolution toward unimodal "old barchan sands" through mobilization, deposition, and stabilization under a moderate-energy wind regime with minimal fluctuations. The second is a dominant bimodal distribution, comprising a well-sorted fine-grained mode mobilized and deposited by low-energy winds with minimal fluctuations, and a well-sorted mode with negative skewness characterized by a developed tail of fine to medium grains mobilized and deposited by medium-energy winds with significant fluctuations. This group includes "slick sands," "deflated sands," and "ridge sands." The third type, which is occasionally observed, is polymodal and very poorly sorted. It is dominated by medium-sized grains accumulated under highly variable wind dynamics or in settings sheltered from remobilization and corresponds to basement sands.

The findings of this paper contribute to ongoing research on wind dynamics in southern Morocco by offering insight into the processes associated with desertification, ranging from bedrock weathering to erosion, transport, and sand deposition.

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Keywords: Desertification, Dune Sands, Wind Dynamics, southern Morocco, granulometric analysis.

1. Introduction

Aeolian processes generate extensive sand sheets and dune fields in arid regions. These sandy deposits require close monitoring, as they may advance more rapidly than desertification, land encroachment, or even the degradation of industrial infrastructure (Gomez et al., 2018; Sur & Chau, 2019). Understanding these deposits is crucial, not only for managing environmental and infrastructural impacts but also for gaining insight into sedimentary processes. As primary aeolian landforms, dunes preserve a record of wind-driven transport and sediment sorting within their source areas. The granulometric and geochemical characteristics of these sediments are essential in aeolian research, providing valuable information on sedimentary processes and provenance (Garzanti et al., 2015; Kalinska-Nartisa et al., 2017; Muhs, 2017; Kasper-Zubillaga et al., 2022). In particular, grain size serves as a key indicator of sediment transport dynamics and offers insights into the origin and composition of sand grains.

Sand grains are fine particles resulting from the fragmentation of rocks or minerals, and they bear witness to the origin and nature of the parent rock from which they originate. They are found in various environments throughout the Earth's crust (Dahnoun and Djadouni, 2020). Grain size analysis is commonly used because it plays a fundamental role in dune ecosystem dynamics, influencing wind transport efficiency and sediment stability. It is also used to assess the shear stress required to initiate and maintain particle movement.

The statistical distribution of granulometric characteristics, such as mean size and asymmetry, also provides a good indicator of how wind dynamics control sand movement patterns. These characteristics are also commonly

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used to infer the aeolian sedimentary environment, given the wide size range. The mixing and sorting of sediment populations vary systematically in response to sedimentary processes, their dynamics , sediment quality, and sediment provenance (Visher, 1969).

Granulometric analysis is a fundamental and widely used method for determining the sedimentary environment, dynamics, depositional mechanisms, and the development of aeolian landforms, as well as the transport and sorting of aeolian particles (Sahu, 1964; Visher, 1969; Wang et al., 2003; Guan et al., 2025). In this paper, we attempted to address some of the above problems by systematically collecting surface sediment samples from the entire Dakhla-Awserd region.

2. Geographical and Climatic Context

The study area liesbetween Dakhla and Awserd in the Saharan provinces of southern Morocco(Figure 1). It is crossed by a north-west-south-east road linking the two towns and is divided into two geographically distinct zones. The first, located in the coastal region of Dakhla, encompasses the bay and peninsula of Dakhla and is characterized by a desert climate tempered by the ocean, which reduces annual temperature variations, allowing mean annual temperatures to range from17°C to 26°C (Sanchez & Martin, 2019).

Coastal areas, softened by oceanic influence, enjoy a generally more moderate climate, while continental regions are subject to harsher climatic conditions. This climatic divergence leads to adaptive responses specific to each environment, both ecological and socio-economical. In the first zone, winds actively shape the relief, constantly reshaping it, and promoting the formation of vast dune fields in perpetual motion (Barcellos et al., 2022). Plant cover is very sparse, dominated by xerophytic and halophytic species, and adapted to saline soils and high evapotranspiration, typical of desert environments (Barbero et al., 1994).

The second zone, the Continental and Saharan region, corresponds to Awserd, located inland and characterized by an extreme desert climate classified as BWh (hot desert climate in the Köppen system). Deprived of the ocean's moderating influence, summer temperatures frequently exceed 45 °C during the day, with high diurnal temperature ranges and annual precipitation below 50 mm (Benattia & Hassan, 2020). Although atmospheric humidity can occasionally enhance water retention, it does not offset the chronic rainfall deficit necessary to support plant life. These harsh conditions, compounded by hot, dry winds, intensify aridity, severely limiting vegetation and making living conditions challenging for local populations (Laurent & Benhammou, 2021).

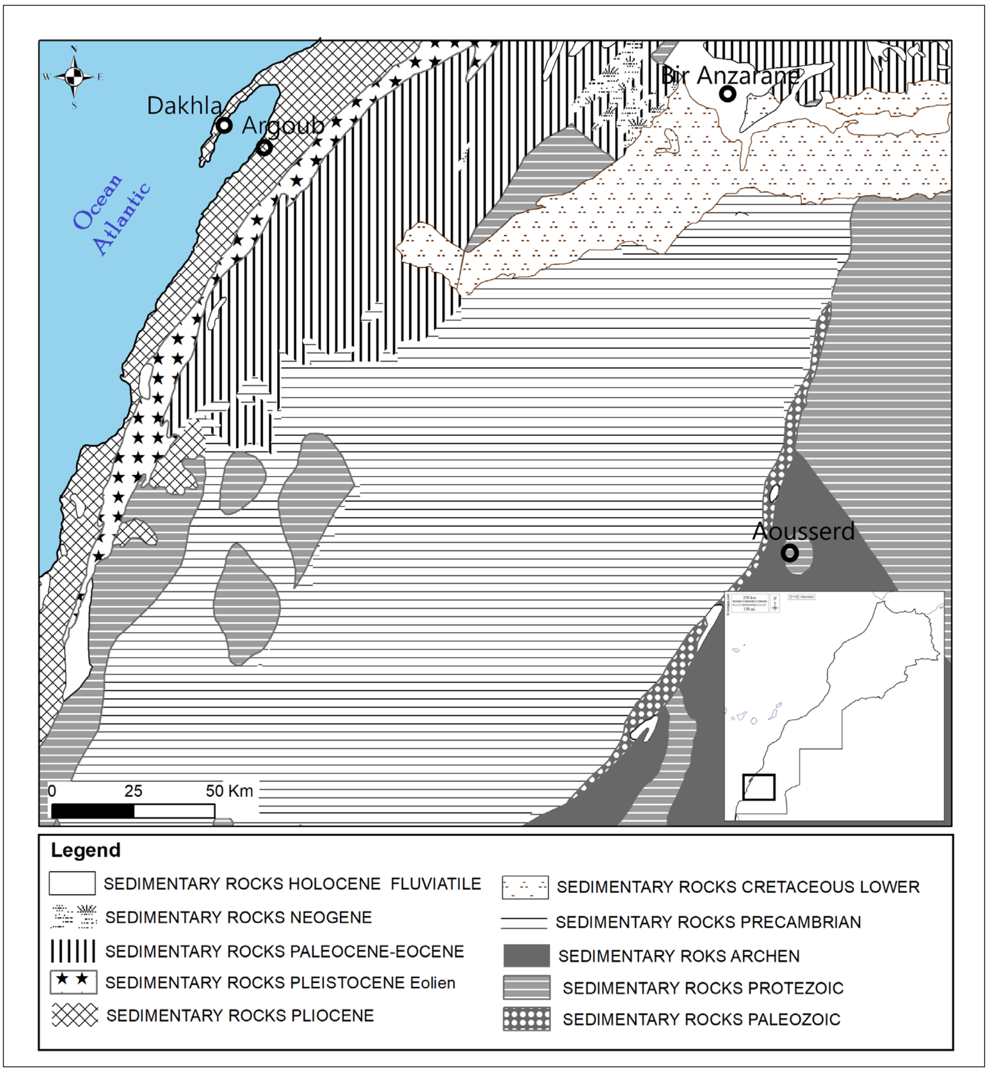

Figure 1. (a) map of Africa locating the Dakhla Peninsula in the westernmost part of the Sahara (Morocco) ; (b) location of surveyed areas in a red square

3. Geological Context

The Dakhla-Awserd region (Figure 2) is organized into four major stratigraphic units. Among these, the Archean formations of the Réguibat ridge are composed mainly of granite, migmatite, and gneiss, with notable concentrations of quartz, feldspar, and mica (Villeneuve, 2008). Wind erosion, active over the long term, has shaped these landscapes by incising the plateaus with ravines and depressions. This process has producedbuttes and cuestas with angular edges, the result of differential erosion: the harder rock layers resist abrasion, while the softer ones disintegrate more rapidly (Fabre, 2005).

The Dakhla region is underlain by an ancient basement known as the R'guibat Ridge, composed of very old rocks such as sandstone, quartzite, and granite (Fabre, 2005; Theveniaut and Dallmeyer, 2009). This basement is overlain by layers of younger sediments, deposited in shallow marine or continental environments (Caby & Kienast, 2009). These sediments are rich in a lot of quartz, which facilitates the formation of sands that are easily transported by the wind. Wind shapes a variety of dunes in the region (Bouziani & Khouja, 2009). Depending on wind strength and direction, dunes can be mobile or more stable, with shapes such as barchanes or ripples (Besler, 1983; Besler, 2008; Pye & Tsoar, 2009). Consequently, local geology and wind dynamics explain the presence and diversity of dunes around Dakhla.y

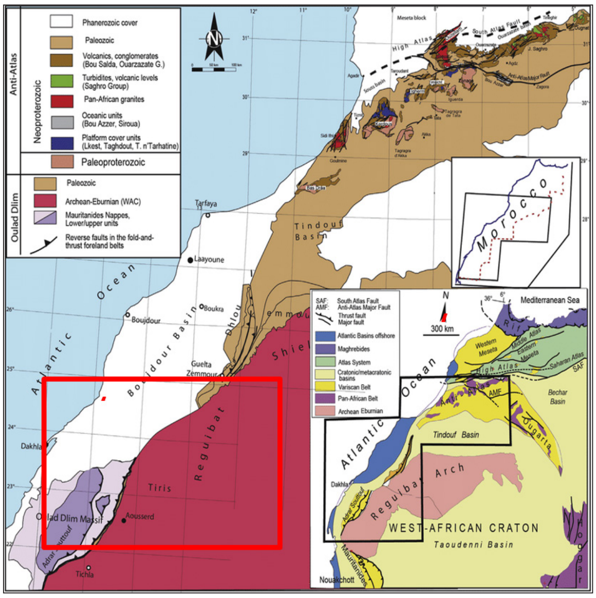

Figure 2. Geological map of the southern part of Morocco, showing the western margin of the R'guibat Shield, its sedimentary cover, and the Precambrian inliers of the Anti-Atlas. The study area is outlined by the red square.

4. Materials and Methods

Sampling sites are shown in Figure 3. For the study and characterization of the granulometric and mineralogical properties of the sandy accumulations in the Dakhla region, two approaches were used. The first approach involved sampling and facies observation: field samples were collected alongside facies identification within and at the periphery of the study area. These missions focused on geological prospecting, facies recognition, and sample collection for laboratory analysis. Each sample was packaged in a labelled plastic bag, allowing rigorous separation and systematic categorization based on criteria such as geographical location, sampling depth, substrate type, and collection date. A Global Positioning System (GPS) was used to locate the sampling sites.

The Quaternary landscapes of the study area are also marked by a wide variety of dune formations: longitudinal dunes aligned with the dominant winds, transverse dunes perpendicular to the prevailing winds, and star-shaped dunes formed by winds with changing directions. Finally, deflation surfaces, where wind erosion removes finer sediments, leaving behind a residual gravel and pebble layer located around the reliefs and plateaus, These surfaces result from strong aeolian erosion, which strips away finer sediments, exposing gravels on the surface. (Bouziani and Khouja, 2009)

4.1. Grain size analysis

Grain-size analysis was performed using the traditional method described by Berthois and Le Calez (1966). The samples were washed, dried in an oven, weighed, and sieved on a column of 12 sieves ranging from 0.5 to 0.063 mm for 20 minutes, following the standard (AG) NF P 18-560. The results of the grain-size analysis for each sample were presented asfrequency curves. The graphical representation used in this study follows the model proposed by Besler (2008) to classify dune sands based on their granulometric evolution using the position and amplitude of their modes. On the x-axis, grain sizes were arranged from the finest to the coarsest using an arithmetic scale, rather than the conventional logarithmic scale. Two units of measurement were used: millimeters (d) and phi (ϕ), which is defined by (Krumbein and Pettijohn, 1938) as $\phi = -\log_2 (d)$. The y-axis differed from the traditional approach by weighting the frequency of each grain-size class by its amplitude, defined as the difference between the maximum and minimum sizes of the class in millimeters. (f (%)/(Δd (mm)). This difference allowed for the derivation of the differential frequencies proposed by Besler (2008), who adjusted raw frequencies based on the size of each class, providing balanced frequencies according to individual sizes. This approach proved more suitable for aeolian processes by correcting the emphasis on coarse grains imposed by the arithmetic scale, allowing the distinction and characterization of various granulometric types of aeolian sands (Besler, 2008). Additionally, the differential frequencies were normalized to represent density curves.

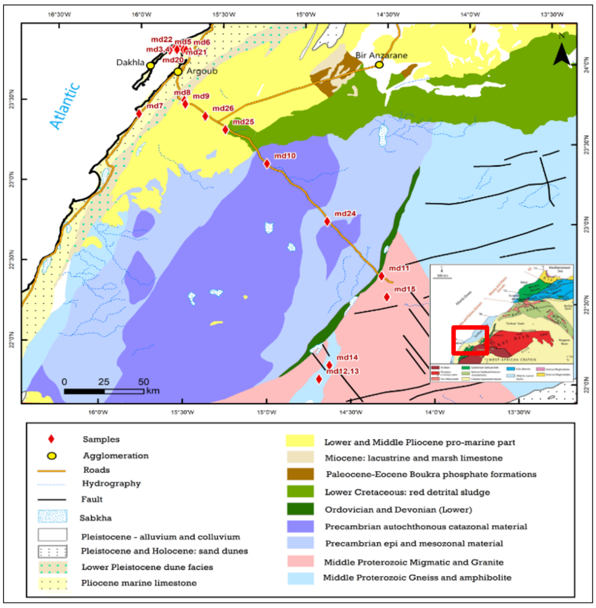

Figure 3. Sampling sites for mineralogical analysis.

The statistical parameters of the grain-size distributions (Folk & Ward, 1957; Folk, 1971) were employed to interpret the transport and sorting characteristics of the dune sands in Dakhla. The parameters expressed in phi (ϕ) are defined as follows:

- Modal size (Mo): The most frequently occurring grain size, indicating the central tendency and homogeneity of the distribution.
- Median size (M): Also referred to as the 50th percentile (ϕ50) or second quartile (Q2), it divides the distribution into two equal parts and provides a robust measure of central tendency, especially for asymmetric distributions.
- Quartiles (Q1 and Q3): On the coarser side of the distribution, grain sizes correspond to cumulative frequencies of 25% and 75%, respectively.
- Centiles (ϕ5, ϕ16, ϕ84, ϕ95): Grain sizes associated with cumulative frequencies of 5%, 16%, 84%, and 95%, respectively, on the coarser side of the distribution

The calculated parameters (Folk and Ward, 1957; Folk, 1971) are as follows:

- Mean size in phi (ϕ): $Mz = \frac{(\phi16+\phi50+\phi84)}{3}$, which is a good measure of the center of a nearly normal and symmetric distribution;
- Standard deviation in phi (ϕ): $\sigma = \frac{(\phi84-\phi16)}{4} + \frac{(\phi95-\phi5)}{6,6}$, also called sorting index, is a good measure of the dispersion around the mean and, consequently, the overall sorting of the grains. It averages the sorting of the 68% of the population centered on the median with that of the 90%;
- Kurtosis coefficient (dimensionless): $KG = \frac{(\phi95-\phi5)}{2,44(\phi75-\phi25)}$ which is a good measure of the shape of the distribution, indicating whether it is more or less pointed or flat. It measures the proportion of the relative deviation in sorting at the tail of the curve compared to its center.
- Skewness coefficient (dimensionless): $Sk = \frac{(\phi16+\phi84-2\phi50)}{2(\phi84-\phi16)} + \frac{(\phi5+\phi95-2\phi50)}{2(\phi95-\phi5)}$, which is a good measure of the symmetry of the distribution. It averages the skewness of the 68% of the population centered on the median with that of the 90%.

The interpretation of the grain-size indices (Table1) is based on the terminology defined by Folk and Ward (1957).

Table 1. Terminology of the granulometric parameters (Folk and Ward, 1957).

Storting index (σ)		Skewness (SK)		Kurtosis (K_G)	
< ø 0.35	Very well sorted	ϕ 1.0 to ϕ 0.3	Strongly fine-skewed	< ø 0.67	Very platykurtic curve
ϕ 0.35 to ϕ 0.5	Well sorted	ϕ 0.3 to ϕ 0.1	Fine skewed	ø 0.67 to ø 0.90	Platykurtic curve
ϕ 0.50 to ϕ 0.71	Moderately well sorted	ϕ 0.1 to ϕ -0.1	Symmetrical	ø 0.90 to ø 1.11	Mesokurtic curve
ϕ 0.71 to ϕ 1.0	Moderately sorted	ϕ -0.1 to ϕ -0.3	Coarse skewed	ø 1.11 to 1.50	Leptokurtic curve
ϕ 1.0 to ϕ 2.0	Poorly sorted	ϕ -0.3 to ϕ -1.0	Strongly coarse-skewed	ø 1.50 to 3.00	Very leptokurtic curve
ϕ 2.0 to ϕ 4.0	Very poorly sorted			> ø 3.00	Extremely leptokurtic curve

5. Results and discussion

5.1. Grain size and aeolian evolution

The approach to the grain-size analysis of the sands from Dakhla follows the methodology used for the sands of Merzouga-Tafilalet (Harchane et al., 2025). Specifically, the methodology developed by Besler (2008) for constructing frequency distribution graphs was used and explained. Based on this methodology, Besler (2008) defined and classified aeolian sands according to the position of the mode and the shape of the distribution, allowing for the interpretation of the aeolian evolution of sandy deposits, originating from alluvial sources primarily from endorheic rivers or other sources such as coastal sands or sands resulting from the weathering of pre-existing rocks, such as granite sands. The various stages of this aeolian evolution, also referred to as aeolian ages, are described by Besler (2008) as follows:

The “young dune sands” represent the first stage in the evolution of the initial sandy stock, which has been mobilized and cleared of silt-clay dust by deflation. They consist of the 63-125 µm fraction mobilized by the winds inland to form small longitudinal dunes and young barkhanes. The second aeolian age is the “active crest sands,” which correspond to the active dune crests formed after the deflation of the very fine sandy fraction (63-125 µm) and the concentration of the fine fraction (125-250 µm). Active crests are found on primary longitudinal and transverse dunes, on barkhanes, and on secondary dunes in the Draa areas after reactivation. The mixture of the preceding two fractions may form “dome sands” through the replenishment of very fine grains. The third aeolian age is the “inactive crest sands,” which corresponds to the inactivation of the dune sands by the progressive loss of the 125-250 µm fraction in favor of the 250-500 µm fraction. This stage is primarily found in the lower parts of longitudinal and transverse dunes, as well as at the edges of barkhane dunes. The preceding stages characterize quasi-stationary dunes in which only the crest is in continuous motion.

The fourth aeolian age is that of the “old barchan sands,” where the 250-500 µm fraction predominates over the fine fractions of the “inactive crest sands.” This aeolian evolution characterizes migrating banchan dunes. According to Besler (2008), the final stage of this aeolian evolution corresponds to a sand with a single mode between 250 and 500 µm, representing the last step in the granulometric evolution of dunes in modern aeolian systems.

Several possibilities for degeneration within this aeolian evolution were highlighted by Besler (2008). These occur when a certain wind stability takes over from mobility. “Sand sheet sands” are characterized by a long tail and a reduced mode of residual coarser grains, which may exceed 1000 µm, associated with a modal 63-125 µm fraction that protects them from deflation. “Deflated sands” are bimodal mixtures between a fine fraction trapped because the sandy stock is no longer mobilized and another medium fraction. “Plinth sands” are characterized by a broad plateau from 63 to 500 µm, sometimes with a slight peak in the fine fractions. These represent a stage of maximal stability, where all deflation is absent, and all imported fractions accumulate.

The analysis of the dune sands of Dakhla is almost devoid of silt-clay fractions (maximum 1.10%), revealing grain size distributions falling into three distinct configurations:

Grain-size homogeneous unimodal sands are rare. Only three samples (Figure 4) with a single mode at 285 µm, were observed. The median grain size for one is 295 µm, and for the other two, it is 342 µm. Their interquartile range is 80110 µm, indicating good sorting. The well-sorted nature is also confirmed by a tight standard deviation, ranging from 75 to 140 µm. These samples exhibit slight positive skewness, indicateded by a flattened tail toward finer grains. Their distribution is leptokurtic to mesokurtic, with an average kurtosis coefficient of 1. These sands indicate good dynamic sorting and consist of a dominant modal fraction of well-sorted medium grains (180-460 or 220-560 µm), with a more or less developed tail of fine to very fine grains (65-180 µm). This distribution suggests mobilization, deposition, and stabilization under a moderate wind regime with little fluctuation.

The correlation of these few unimodal aeolian sands from Dakhla with the types defined by Besler (2008) allows their interpretation as the result of ongoing aeolian evolution, transitioning from “inactive crest sands” to “old barchan sands” in a unimodal state.

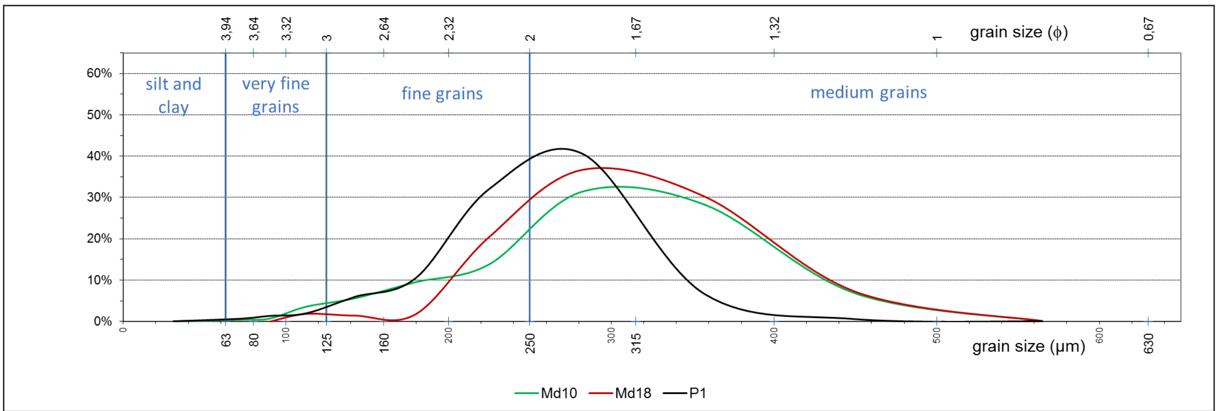

Figure 4. Typical unimodal frequency curves for Dakhla dune sands.

The majority of the analyzed sands exhibit bimodal distributions with distinct well-separated modes, corresponding to mixtures of two homogeneous grain-size subpopulations (Fig. 6a). These two subpopulations were separated for the same reasons and in the same manner as the sands of Merzouga-Tafilalet (Harchane et al., 2025), assuming that any heterogeneous grain population consists of homogeneous subpopulations in terms of their origin or nature (Folk, 1971). The total bimodal samples were thus graphically segmented, around 180 µm, into homogeneous unimodal sub-samples (Figure 5) with significant representative statistical parameters and distributions reflecting their individual origins and evolutions.

These two modes , with few exceptions, occupy well-defined and relatively stable positions (Fig. 6a): the first around 142 µm, and the second around 225 µm. They thus represent two grain fractions: the fine grain fraction (90-180 µm) and the fine-to- medium grain fraction (180-350 µm), with, in addition, a more or less developed tail, extending to 600 µm and a very reduced and minor tail of very fine grains (65-90 µm). The main fractions are mixed in various proportions, with each fraction potentially being minor or major. Only one sample exhibits a predominant very fine mode of 112 µm, associated with a very reduced fine–to-medium mode at 225 µm and a long low tail extending to 500 µm.

The analysis of the fine-grain fraction, with a mode of 142 µm, showed a median size, ranging between 130 and 165 µm, and an average of 158 µm. The average grain size in this fraction ranges from 131 to 165 µm, with an average of 157 µm and a mean standard deviation of 17.5,ranging from 10 to 27 µm, and an interquartile range of 15 µm. The distribution is leptokurtic to very leptokurtic, with a mean kurtosis coefficient of 1.8. It is symmetrical to slightly asymmetrical toward coarser or finer grains. These grains would therefore be very well-sorted sands, mobilized and deposited by low-energy winds with minimal fluctuations.

The grains in the fine–to-medium fraction, with a mode of 225 µm, have median sizes ranging from 250 to 340 µm, with an average of 296 µm. Their average sizes range from 257 to 341 µm, with an average of 302 µm, a mean standard deviation of 80 µm (ranging from 47 to 106), and an interquartile range of 85 µm. Their distribution can be leptokurtic, mesokurtic, or platykurtic, with a mean kurtosis coefficient of 1.2. It is weakly or strongly skewed toward the coarser grains, due to the more or less developed tail of coarse grains. These characteristics correspond to well-sorted sands, mobilized and deposited by winds of medium energy, with noticeable fluctuations.

Correlating the segmented distributions of the bimodal aeolian sands of Dakhla with the types defined by Besler (2008) indicates that they represent a mixture of two dominant components (Figure 5). The very fine to fine modal fraction corresponds to the "active crest sands" type in most cases. Only one sample shows a very fine fraction of the "young dune sands" type (Md11), and another shows the "dome sand" type (Md3), indicating a replenishment of very fine sands. The fine–to-medium modal fraction results from a gradual evolution from the "inactive crest sands" (Md3 and Md25) to the "old barchan sands" (Md19 and Md22) and the "ridge sands" (Md11 and Md24), with stages visible from one sample to another.

These fractions form a heterogeneous mixture in varying proportions (Figure 5). Each fraction represents a specific wind kinetic energy responsible for its mobilization. The lowest energy in the studied area is responsible for the deposition of the "young dune sands," while the highest energy brings the "ridge sands," passing through the "active crest sands," then "inactive crest sands," and finally the "old barchan sands." The following mechanisms could act jointly or differentially to generate these two-mode mixtures, which are characteristic of the aeolian sands in the study area:

1- Simultaneous deposition of the two modal fractions due to alternating wind dynamics over short durations, explaining their coexistence (Figure 5, all samples).

2- Gradual evolution between stages during a change in wind regime, with winds becoming increasingly stronger, incomplete deflation of the finer fraction, and deposition of the coarser fraction. This mechanism would explain the observed differences between samples for modal fractions of the same category (Figure 5, all samples).

3- Degeneration of aeolian evolution, from "old barchan sands" to fine sands undergoing deflation (Fig. 5a, Md19 and Md22), toward aeolian ages characteristic of wind stability, where fine sands are no longer swept away, while stronger winds continue to bring coarser grains and readjust the distributions. Sample Md11, with a very fine mode at 112 µm, would likely be a "sand sheet sand," while Md3 and Md25 would correspond to "deflated sands."

4- If the occasional stronger winds responsible for the coarse tails become more regular, the coarse mode increases in amplitude, and the sand would become a "ridge sand" (Figure 5a, Md24).

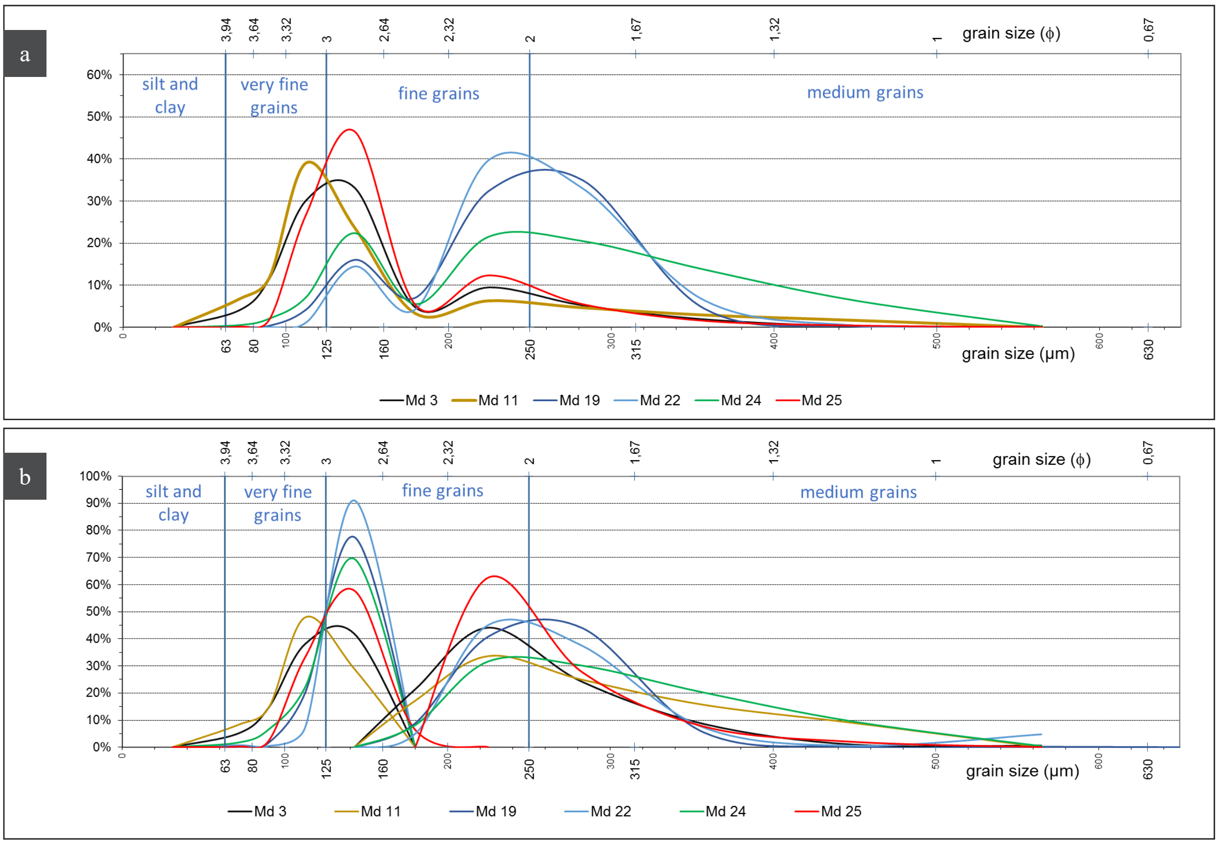

Figure 5. (a) typical bimodal frequency curves for Dakhla dune sands. (b) Segmented modes of the same sands.

Some sands from the study area (Figure 6) exhibited a highly heterogeneous grain-size distribution with a multimodal frequency curve that is very platykurtic, indicating a near absence of genetic sorting. These distributions range from 63 µm to 700 µm, with a median of 300-480 µm, an average of 380 µm, a first quartile of 400-550 µm, and a third quartile of 240-380 µm. Their interquartile range is very wide, from 135 to 270 µm, with an average of 185 µm, indicating poor sorting of these sands. These sands are thus composed of a large, poorly sorted fraction of medium grains (250-700 µm), followed by an equally poorly sorted fraction of fine grains (125-250 µm), in addition to a very small amount of very fine grains (65-125 µm). These sands were likely accumulated under the influence of vortex, multidirectional winds, or winds with highly variable dynamics acting simultaneously. The presence of obstacles could also explain this lack of sorting. They likely correspond to the "plinth sands" of Besler (2008).

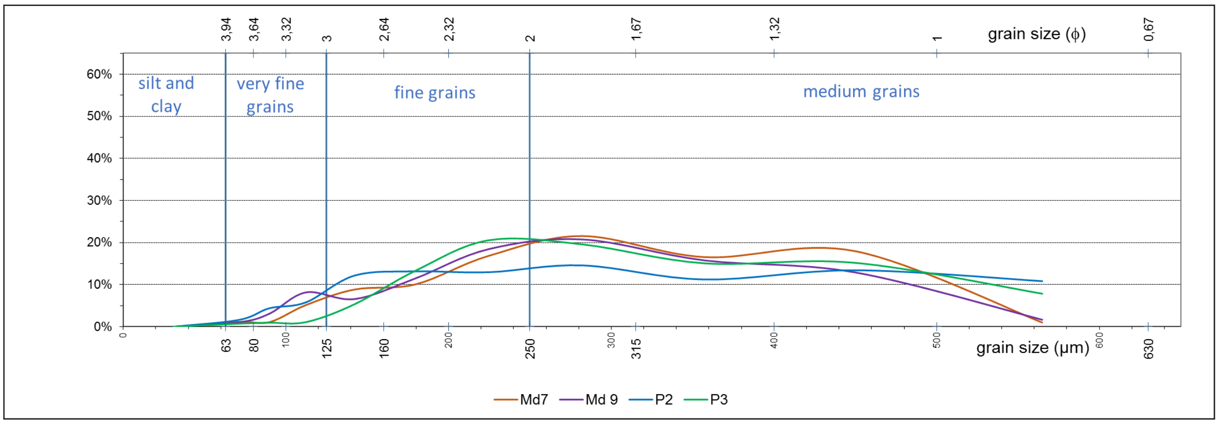

Figure 6. Typical multimodal frequency curves for Dakhla dune sands.

The analysis of the very fine–to-fine sand fractions of the heterogeneous samples (Figure 5) revealed sharp-peaked sand curves, indicating the mobility of thesesands. The aeolian ages of these sand fractions also supported the mobility of the studied sands, as it is well known that sands from young dunes with active and inactive crests are always in aeolian mobility, that is, a sorting factor responsible for the good classification of transported and deposited sands, and it is especially effective when it acts on fine grains (Besler, 1983).

In contrast, the frequency analysis of the homogeneous samples (Figure 4) and the fine-to-medium sand fractions of the heterogeneous samples (Figure 5) showed broader, more peaked curves for fine-to-medium sand, with a coarser sand tail, indicating lower mobility. The aeolian ages of these samples and sand fractions are also consistent with the relative stability of the wind regime under which they were accumulated.

For confirmation, the response diagram from Besler (1983) was used in Figure 7. This diagram, derived from the diagram of Friedman (1961), allows a quantitative distinction between mobile, stabilized, and residual aeolian sands, as well as fluvial sands. It is a binary diagram that plots the mean grain size (Mz) in Φ, against the sorting index (σ) in Φ. The mean size indicates the average kinetic energy of the transport and deposition agent, the sorting index, or standard deviation. It represents the variability of this energy around the mean. Because these two parameters can be strongly influenced by sample heterogeneity, meaning the association of several transport and deposition agents or grain sources (Besler, 1983), the parameters calculated fromthe segmented fractions were used for the heterogeneous samples in the diagram.

Overall, the mean grain sizes of Dakhla sands (Figure 5a) align with those observed in the Moroccan desert by Benalla (2003), Boudad (2004), and Harchane et al. (2025). Their sorting index is also in agreement with those of well-sorted continental dune sands (less than 0.5) described by Friedman (1961).

5.2. The Response Diagram

The response diagram (Figure 7), thanks to the small size and strong sorting of the fractions, confirmed that the very fine fractions are indeed aeolian sediments in the process of mobilization. The fine fractions lie between mobility and aeolian stability, with their sizes corresponding to the threshold for sand movement. The medium fractions are clearly within the stability zone, on the edge of the residual zone, given their sizes that exceed the threshold mobilization speed.

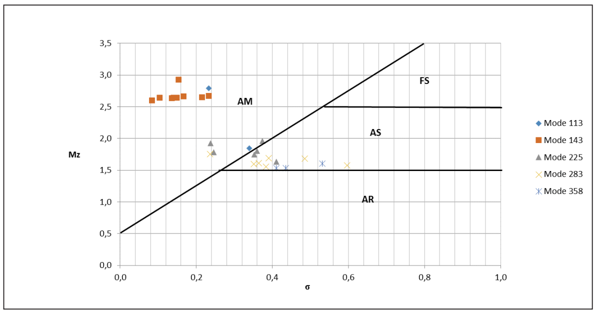

Figure 7. The response diagram (Besler, 1983) of Dakhla dune sand segments: Fluvial Sands (FS), Aeolian Mobility Sands (AM), Aeolian Stability Sands (AS), Aeolian Residuals (AR).

6. Conclusion

The aeolian evolution of the sands in the Dakhla region has been interpreted through detailed granulometric analysis, highlighting the dominance of wind-driven processes in forming of dune complexes. Although various modes of sediment transport have contributed to sand accumulation, aeolian activity remains the principal agent, sorting the grains into distinct fractions: very fine-grained (63–100 µm), fine (100–180 µm), and fine–to-medium (180–350 µm and beyond).

These findings highlight distinct granulometric distribution types within the Dakhla sands, reflecting differences in sediment transport and depositional conditions. Based on Besler's (1983, 2008) response diagrams, the observed grain-size fractions correspond to varying degrees of aeolian mobility and stability: the very fine sands indicate active wind transport, the fine fraction marks the transitional threshold between mobility and stability, and the coarser fractions are largely stable, representing residual, relict accumulations. This interpretation clarifies how wind dynamics shape dune evolution and the spatial variability of sediment deposits in the region. Three main granulometric distribution types were identified:

1. Unimodal distributions, relatively rare, show well-sorted medium grains and slight positive skewness, corresponding to stabilized “old barchan sands” shaped by moderate, steady winds.

2. Bimodal distributions, the most common, combine fine and fine-to-medium fractions, indicating alternating wind regimes of varying energy. These sands represent transitional aeolian ages between “old barchan sands” and “ridge sands.”

3. Polymodal distributions, less common, consist of poorly sorted grain mixtures ranging from 65 to 700 µm. Their chaotic structure suggests deposition under turbulent, multidirectional winds or in sheltered environments, consistent with Besler’s “plinth sands.”

These findings underscore the complexity of aeolian processes in shaping the sandy Dakhla’s landscape. The diverse grain-size distributions and sedimentary structures reflect both past and present wind dynamics. Overall, the dune sands preserve a detailed archive of aeolian activity over time, illustrating stages of mobilization, deposition, and stabilization that define their “aeolian ages.”

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Conflict of Interests

The authors declare that they have no conflicts of interest concerning the publication of this paper.

References

Barbero, M., Loisel, R., & Quézel, P. (1994). Écologie et adaptations des plantes en zone saharienne. Actes du Congrès de l’Écologie Méditerranéenne, 23–30.

Barcellos, A. F., Tavares, A. C., Oliveira, P. T. S., & Sano, E. E. (2022). A global Köppen–Geiger climate classification map based on remote sensing data. International Journal of Climatology, 42(1), 186–202. https://doi.org/10.1002/joc.7253

Benalla, M., et al. (2003). Les dunes du Tafilelt (Maroc): dynamique éolienne et ensablement des palmeraies. Sécheresse, 14, 73–83.

Benattia, M., & Hassan, A. (2020). Impact des changements climatiques sur le climat saharien d’Awserd. Bulletin de la Société Météorologique du Maroc, 12(4), 87–98.

Berthois, L., & Le Calez, Y. (1966). Etude sédimentologique des dépôts à « Jullienella fœtida » de la région d’Abidjan. Bulletin du B.R.G.M., 1, 44–55.

Besler, H. (1983). The response diagram: Distinction between aeolian mobility and stability of sands and aeolian residuals by grain size parameters. Zeitschrift für Geomorphologie N.F., Suppl-Bd., 45, 287–301.

Besler, H. (2008). The Great Sand Sea in Egypt. Developments in Sedimentology, 59. Elsevier.

Boudad, L. (2004). Les formations sédimentaires du pléistocène supérieur et de l’holocène du Tafilelt (Sud-Est du Maroc): Géochronologie, stratigraphie et paléoenvironnement (Thèse de 3ème cycle). Université Moulay Ismail, Meknès, Maroc.

Bouziani, A., & Khouja, M. (2009). Formations quaternaires et systèmes dunaires de la région de Dakhla-Awserd. Revue Marocaine de Géomorphologie, 4(1), 33–47.

Caby, R., & Kienast, J. R. (2009). Neoproterozoic and Hercynian metamorphic events in the Central Mauritanides: Implications for the geodynamic evolution of West Africa. Journal of African Earth Sciences, 53, 122–136. https://doi.org/10.1016/j.jafrearsci.2008.09.004

Dahnoun, K., & Djadouni, F. (2020). Effects of heavy-metal pollution on soil microbial community, plants, and human health. Jordan Journal of Earth and Environmental Sciences, 11(3), 234–240. http://jjees.hu.edu.jo/files/Vol11No4/JJEES_Vol_11_No_4_P1.pdf

Fabre, J. (2005). Géologie du Sahara occidental et central. Tervuren African Geosciences Collection, MRAC Tervuren, Belgique.

Folk, R. L. (1971). Longitudinal dunes of the northwestern edge of the Simpson Desert, Northern Territory, Australia. I. Geomorphology and grain size relationships. Sedimentology, 16, 5–54.

Folk, R. L., & Ward, W. C. (1957). Brazos River bar (Texas): A study in the significance of grain size parameters. Journal of Sedimentary Research, 27, 3–26.

Friedman, G. M. (1961). Distinction between dune, beach, and river sands from their textural characteristics. Journal of Sedimentary Research, 31(4), 514–529. https://pubs.geoscienceworld.org/sepm/jsedres/article/31/4/514/95526

Garzanti, E., Resentini, A., Andò, S., Vezzoli, G., Pereira, A., & Vermeesch, P. (2015). Physical controls on sand composition and relative durability of detrital minerals during ultra-long-distance littoral and aeolian transport (Namibia and southern Angola). Sedimentology, 62, 971–996. https://doi.org/10.1111/sed.12169

Gomez, C., Garcia, A., & Smith, J. (2018). Aeolian processes and dune dynamics in arid environments: A global synthesis. Geomorphology, 312, 1–15. https://doi.org/10.1016/j.geomorph.2018.04.005

Guan, C., Hasi, E., & Tang, K. S. (2025). Grain size characteristics of the reticulate dunes of the Hobq Desert. Journal of Arid Environments, 226. https://doi.org/10.1016/j.jaridenv.2024.105279

Harchane, S., Azzouzi, N., El Hammichi, F., Tabyaoui, H., & El Hammouch, N. (2025). Mineral composition and aeolian evolution of dune deposits in Merzouga-Tafilalet, South-Eastern Morocco. Studia Quaternaria, 42, 27–40. https://doi.org/10.24425/sq.2025.154324

Muhs, D. R. (2017). Evaluation of simple geochemical indicators of aeolian sand provenance: Late Quaternary dune fields of North America revisited. Quaternary Science Reviews, 171, 260–296. https://doi.org/10.1016/j.quascirev.2017.07.007

Kasper-Zubillaga, J. J., Arellano-Torres, E., Alvarez Sánchez, L. F., Carlos-Delgado, L., Martínez-Serrano, R., & Jiménez,

P. B. (2022). Implications of polymodal distributions in the grain size parameters of coastal dune sands (Oaxaca, Mexico). Sedimentary Geology, 437, 106189. https://doi.org/10.1016/j.sedgeo.2022.106189

Kalinska-Nartisa, E., Alexanderson, H., Nartiss, M., Stevic, M., & Kaiser, K. (2017). Sedimentary features reveal transport paths for Holocene sediments on the Kristianstad coastal plain, SE Sweden. GFF, 139(2), 147–161. https://doi.org/10.1080/11035897.2017.1290675

Krumbein, W. C., & Pettijohn, F. J. (1938). Manual of sedimentary petrography. Appleton-Century-Crofts.

Laurent, C., & Benhammou, F. (2021). Conditions de vie dans le désert saharien: Études socio-environnementales. Sociologie du Maroc, 19(2), 99–115.

Pye, K., & Tsoar, H. (2009). Aeolian sand and sand dunes (2nd ed.). Springer. https://doi.org/10.1007/978-3-540-85910-9

Sanchez, J., & Martin, L. (2019). Les dynamiques climatiques du littoral de Dakhla. Annales Marocaines de Climatologie, 14, 65–78.

Sur, R., & Chauhan, P. (2019). Aeolian transport and dune migration using remote sensing and GIS techniques: Case study from the Thar Desert, India. Aeolian Research, 39, 24–34. https://doi.org/10.1016/j.aeolia.2019.02.002

Theveniaut, H., & Dallmeyer, R. D. (2009). Chronologie et déformation des reliefs de l'Adrar Souttouf et du massif de Réguibat. Precambrian Research, 167(1–2), 104–118. https://doi.org/10.1016/j.precamres.2008.10.003

Villeneuve, M. (2008). Review of the orogenic belts on the western side of the West African craton: The Bassarides, Rokelides and Mauritanides. In N. Ennih & J.-P. Liegeois (Eds.), The boundaries of the West African craton (Geological Society of London, Special Publications, 297, pp. 169–201). https://doi.org/10.1144/sp297.8

Visher, G. S. (1969). Grain size distributions and depositional processes. Journal of Sedimentary Research, 39(3), 1074–1106. https://doi.org/10.1306/74D71D9D-2B21-11D7-8648000102C1865D

Sahu, B. K. (1964). Depositional mechanisms from the size analysis of clastic sediments. Journal of Sedimentary Research, 34(1), 73–83. https://doi.org/10.1306/74D70FCE-2B21-11D7-8648000102C1865D

Wang, X., Dong, Z., Zhang, J., Qu, J., & Zhao, A. (2003). Grain size characteristics of dune sands in the central Taklimakan Sand Sea. Sedimentary Geology, 161(1–2), 1–14. https://doi.org/10.1016/s0037-0738(02)00380-9