Journal of Environmental & Earth Sciences
https://journals.bilpubgroup.com/index.php/jees

ARTICLE

Contribution of Granulometric Analyses to the Understanding of Wind Dynamics in the Figuig-Bouarfa Region (Eastern Morocco)

Smail Harchane * , ***Nassareddine Azzouzi, Fatima El Hammichi, Hassan Tabyaoui, Abderrahim Lahrach***

Geo-Resources and Environment Laboratory, Sidi Mohammed Ben Abdellah University, Fez, Morocco

ABSTRACT

Morocco, like many arid countries, is facing desertification, particularly in its southern and southeastern regions. A clear indication of this process is the movement of sand dunes in the southern part of the country. Studying wind dynamics in this area provides insights into the conditions and processes driving desertification, including sand erosion, transport, and deposition. This study focuses on the dune sands in eastern Morocco, analyzing their granulometric properties to better understand transport mechanisms and wind dynamics in the region. Granulometric analysis was performed on various sand deposits to investigate aeolian transformations in the area. The results show that the sand deposits in the eastern region consist primarily of a well-sorted dominant granulometric fraction, along with a minor fraction. The sand grains range in size from very fine to medium (150 to 218.8 µm) and are classified as having good to fairly good sorting (36 to 114.2 µm). The grain size symmetry varies from weak to strong, with a range of −0.34 to 0, indicating a tendency toward either finer or coarser grains. The grain size distribution varies, ranging from platykurtic to very leptokurtic (0.7 to 2.15). The deposits display a unimodal distribution with a minor tail on both sides of the dominant mode, suggesting significant wind deflation. Five particle size classes were identified, reflecting the sands' evolution under wind dynamics.

Keywords: Desertification; Sand Dune; Aeolian Dynamics; Granulometric

*CORRESPONDING AUTHOR:
Smail Harcahne, Geo-Resources and Environment Laboratory, Sidi Mohammed Ben Abdellah University, Fez, Morocco;
Email: Smailharchane@gmail.com

ARTICLE INFO
Received: 13 February 2025 | Revised: 3 March 2025 | Accepted: 18 March 2025 | Published Online: 6 May 2025
DOI: https://doi.org/10.30564/jees.v7i5.8727

CITATION
Harchane, S., Azzouzi, N., El hammichi, F., et al., 2025. Contribution of Granulometric Analyses to the Understanding of Wind Dynamics in the Figuig-Bouarfa Region (Eastern Morocco). Journal of Environmental & Earth Sciences. 7(5): 158–174. DOI: https://doi.org/10.30564/jees.v7i5.8727

1. Introduction

Desertification, defined by the United Nations Convention to Combat Desertification (UNCCD) as "land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities", is a major global environmental and ecological problem [1]. Globally, desertified land covers 3.6×10^7 km², representing 24.1% of the earth's surface and affecting around one-sixth of the world's population, many of whom live in poverty.

Combating desertification is crucial to global poverty reduction, and involves understanding its causes and effects [2], as well as monitoring and assessing its progress [3].

In recent years, the concept of desertification has been associated with the loss of ecosystem services resulting from anthropogenic disturbance and/or climatic variations in dryland ecosystems [1].

Desert regions are increasingly facing imminent threats and are becoming vulnerable to the effects of climate change, urbanization, land degradation, water scarcity and other factors [4]. This region was chosen as a model for assessing dune migration, as it is mainly influenced by wind dynamics, which play a decisive role in the dune formation process, as observed in the eastern part of the Moroccan Great Sahara Desert [5].

Wind processes generate vast expanses of sand and dunes in arid zones. They require monitoring, as they often exacerbate problems of desertification or land encroachment and can harm industrial and tourism infrastructures [6].

Cases of desertification and their severity vary from region to region, depending on the quality of interactions between the natural environment and human activity. The United Nations classification of desertification identifies four levels of severity. Aeolian processes, named after the Greek god of wind, refer to the movement of air, encompassing erosion, transport and deposition resulting from wind movement on the Earth's surface [7].

According to Sbai and Mouadili [8], dunes in the areas studied reach a maximum height of 4 to 5 meters. They are of the transverse type, with an asymmetrical cross-sectional profile. Most have elongated crests oriented approximately WNW-ESE or WSW-ENE, with a steep north-facing slope, indicating the influence of southerly winds. However, these dunes are arranged in imperfectly aligned ridges with variable orientations. Their interlocking form complex dune systems, reflecting the combined effects of winds from multiple directions.

Grain size analysis is commonly used by sedimentologists to classify sedimentary environments and understand transport dynamics. Grain size is also a crucial abiotic component of dune ecosystems, as it allows assessment of the shear stress required to initiate and maintain particle movement. In addition, mineralogical and geochemical studies of dune sands provide valuable information on the origin and evolution of aeolian sand formations.

Variations in grain size in coastal and desert dune sands have been extensively studied to understand transport and deposition mechanisms [9]. For example, the phenomenon of dune sand coarsening may result from wind deflation of fine grains, leaving behind a coarser sand fraction [10].

This study aims to determine: (1) the particle size distribution in different sand stocks, (2) the variability of particle size characteristics, (3) the establishment of relationship between the different particle size indices, and (4) the different stages of particle size evolution.

2. Geographical and Climatic Context

The study area lies in Morocco's eastern High Atlas (**Figure 1**), bounded to the north by the Hauts Plateaux and to the south by the pre-Saharan regions of the Colomb-Béchar basin. It represents an extension of the limestone High Atlas, including the Midelt, Rich and Anoual massifs to the west, and extends eastwards in a northeast/southwest direction to join the Algerian Saharan Atlas. This region is characterized by alternating anticlines and tabular massifs, separated by closed plains filled with alluvial deposits dating from the Quaternary period.

Hydrogeologically, the plain contains several aquifers:

- The groundwater of the palm groves;
- The groundwater of the Tisserfine-El Arja plain;
- The deep aquifer composed of fractured and karstic Liassic limestone;
- The potential aquifer of the Dogger.

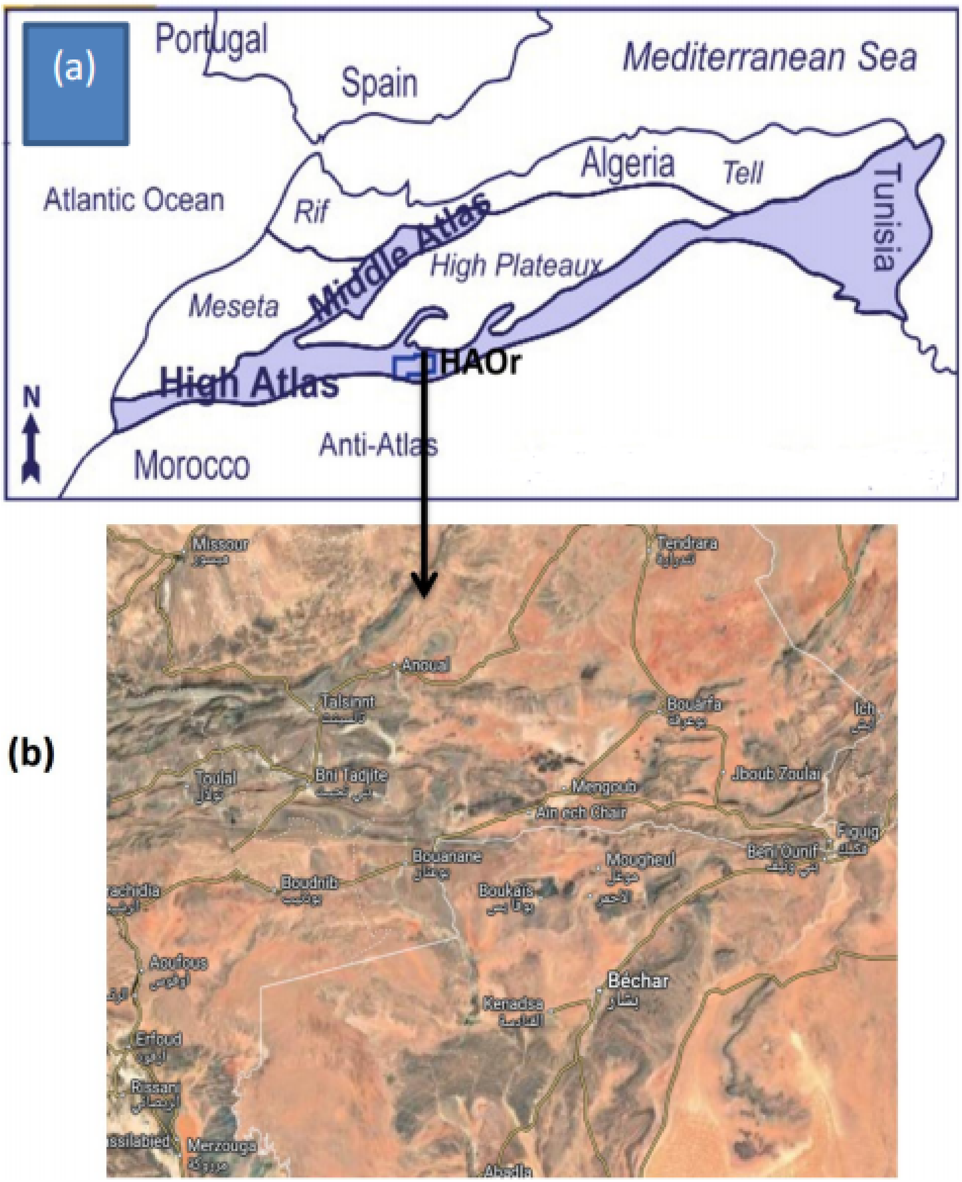

Figure 1. (**a**) Geological situation of the Eastern High Atlas (HaOr) (modified after Teixell and Koyi [11]). (**b**) Satellite map of the study area in the Eastern High Atlas (Google maps).

The wind roses take on a star shape, indicating a predominance of winds blowing from the collateral points: southwest, northwest and northeast [8]. In summer, easterly winds are the most frequent. Chergui, a wind blowing from east to southeast, is associated with high temperatures, sometimes leading to a temporary drop in temperature, usually in summer, lasting from a few hours to a few days. Frequent and sometimes violent winds blow throughout the year, sometimes reaching speeds in excess of 100 km h^{-1} (**Figure 2a**), causing sandstorms. The region is dominated by an arid climate, with cold winters and hot summers. Precipitation is low, averaging 120 mm over a 22-year period (2000–2022). Annual precipitation varies considerably from one year to the next, with temperatures ranging from 38 °C to 45 °C, and reaching as high as 48 °C. Precipitation distribution also varies significantly from month to month (**Figure 2b**).

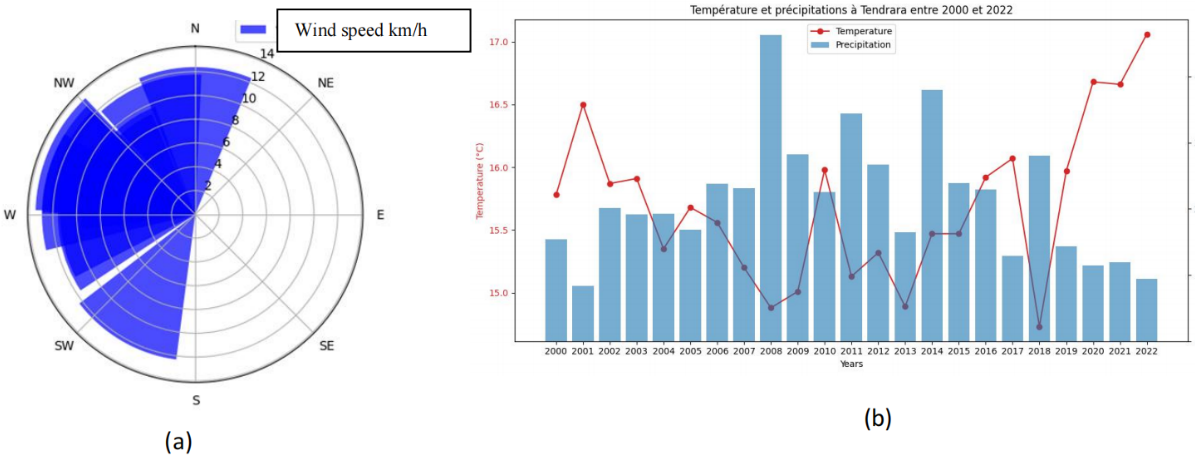

Figure 2. (**a**) Wind rose at Tendrara in 2019; (**b**) Temperature and precipitation at Tendrara between 2000 and 2022.

3. Geological Setting

From a geological point of view, according to Michard[12], the Eastern High Atlas forms a depression corresponding to the Tamlelt window, 120 km long and 50 km wide. In this region, Precambrian and Paleozoic terrains outcrop in the form of windows. This depression is delimited by Meso-Cenozoic formations, which also appear in the center of the window in the form of control lenses. The Meso-Cenozoic Atlassic overburden outcrops on a basement mainly composed of Cambrian, Ordovician and Silurian fossiliferous terrains, as well as extensive lenses of Precambrian basement (**Figure 3**).

Structurally, the Eastern High Atlas is characterized by polyphase faults[13–15]. Since the Jurassic, the region has undergone extensional phases with NNE-SSW and NE-SW distensional directions, resulting in significant dislocation of Jurassic dolomites and limestones. The Tertiary compressional phase, responsible for the uplift of the entire High Atlas chain, reactivated the main faults, transforming them into reverse faults and, locally, strike-slip faults, such as those affecting the Tamlelt plain.

Regarding magmatism, according to Milhi et al.[16], several Hercynian and Triassic veins (microgranites, microgabbros, diabases) cross the series. The microgranites are little altered and composed of quartz, potassium feldspar (orthoclase), and microcline. The green rocks, which are fairly weathered, consist of microgabbros and diabases, with a microlithic background crystallized with minerals such as epidote, plagioclase, pyroxene (augite), and pyrite. Amphibolite veins are rare.

From a metallogenic standpoint, mining studies have mainly focused on the main mines, namely manganese at Bouarfa, barite at Zelmou and gold-bearing copper at Menhouhou. Other showings and occurrences have only been investigated on an ad hoc basis as part of regional surveys.

To the best of our knowledge, the main "academic" works carried out in the region are those of Sharp et al.[17–23]. As far as geological mapping is concerned, and in addition to the reduced scales of 1/1,000,000 (covering the whole of the national territory) and 1/500,000 (covering the northern part of the country), the area has been mapped at 1/200,000 by Du Dresnay[24] and at 1/50,000 by Milhi et al.[16].

4. Materials and Methods

Two approaches were used to study and characterize the grain size distribution of sandy accumulations in the eastern regions (**Figure 4**). The first approach involved sampling and facies observation: ten samples were collected in the field on the surface, supplemented by identification of the facies encountered and bordering the study area. These missions focused on the study of geological surveys, facies recognition and the collection of samples for laboratory analysis. The samples, placed in labelled plastic bags, were separated for subsequent analysis. A Global Positioning System (GPS) was used to locate the sampling sites and measure the height of the dunes in relation to sea level (**Figure 5**).

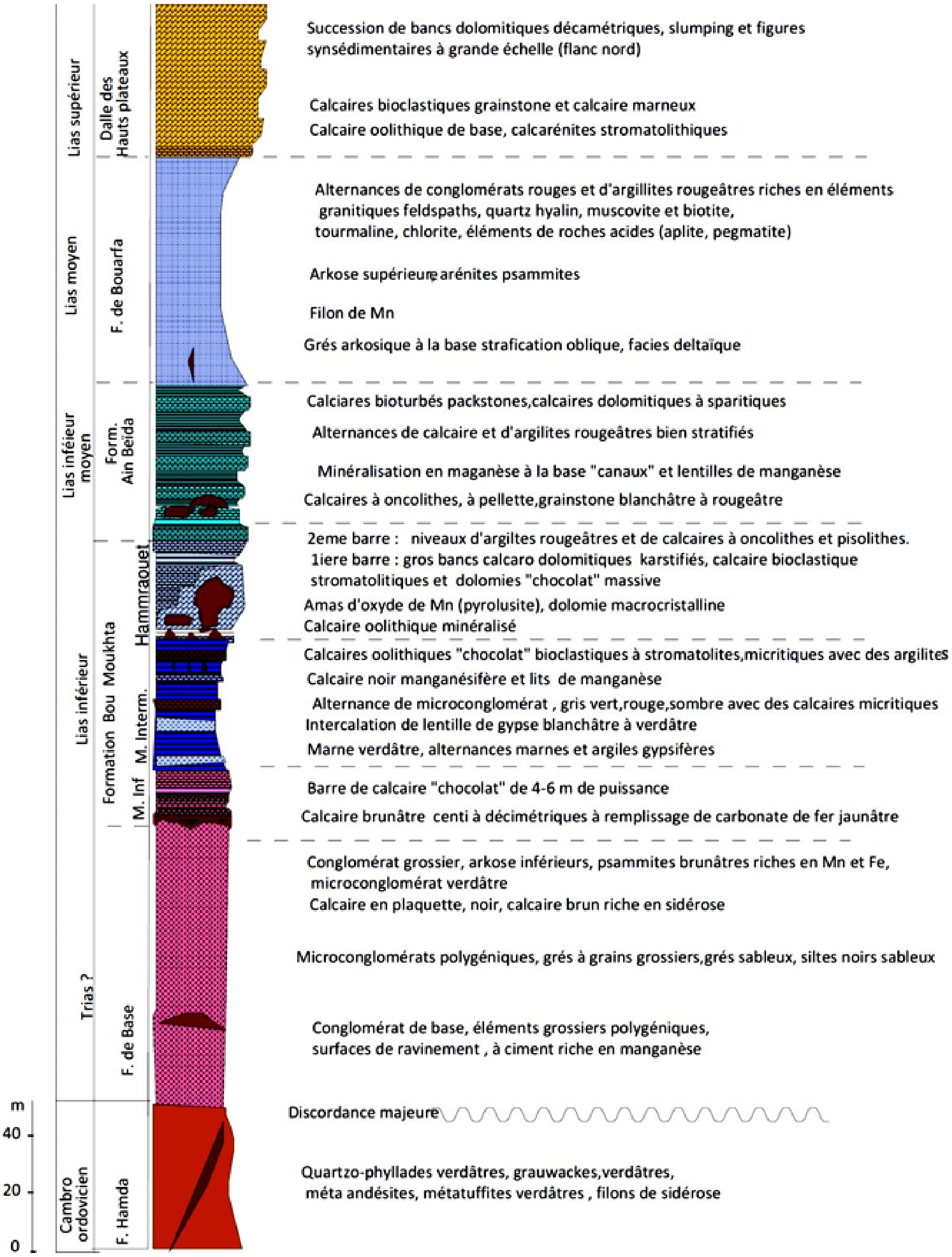

Figure 3. Stratigraphic column of the Bouarfa sector by Bahi et al. [25].

The aim of this study is to understand sandy accumulations in the Oriental region. A dynamic and sedimentological study was undertaken as part of the second approach to this research, which includes laboratory analyses, including granulometry to determine grain size distribution, morphoscopy to assess the shape and appearance of quartz grains, X-ray mineralogy, and heavy mineral extraction by bromoform, to reveal the textural and mineralogical characteristics of sand stocks. These studies were undertaken by Harchane et al. [26] on this and other regions of Morocco.This article focuses solely on the granulometric analysis of the sand samples from the Oriental region.

Figure 4. Sandy accumulations in the study area.

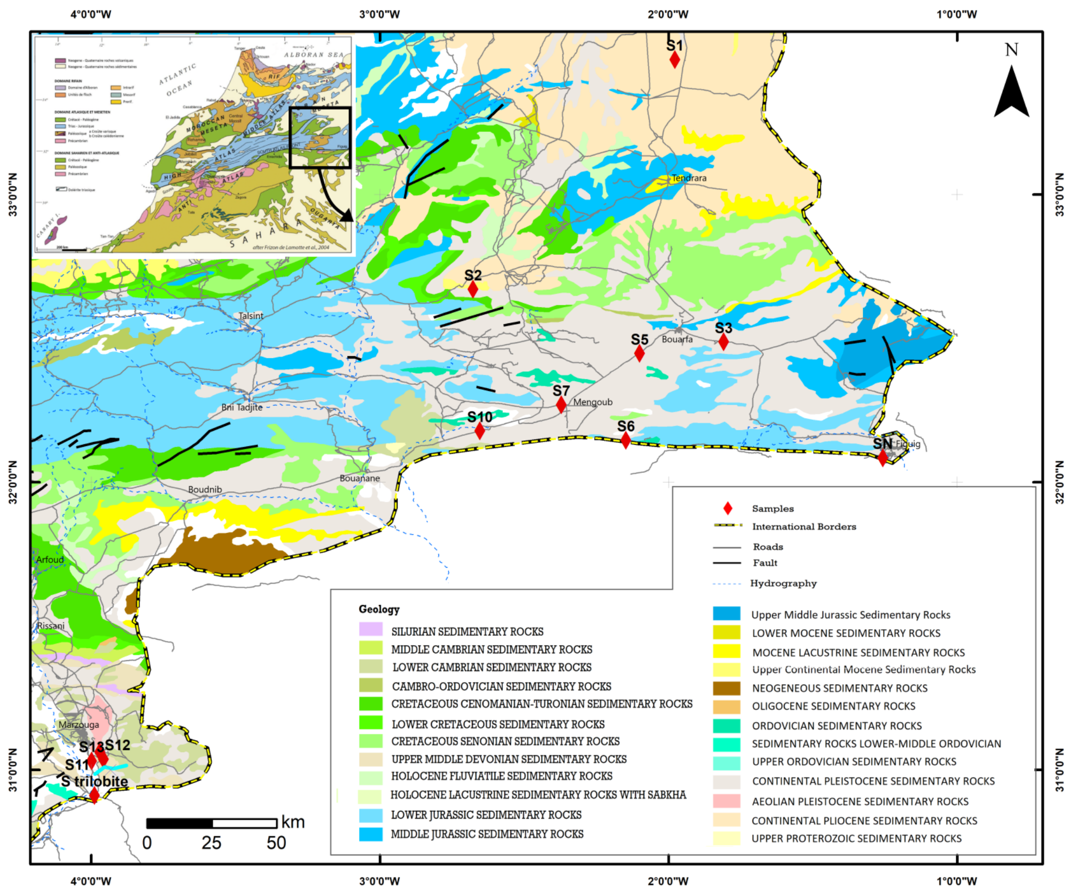

Figure 5. The sampling sites on the geological map.

4.1. Granulometric Analysis

The granulometric analysis was conducted using the traditional method described by Berthois and Le Calez [27]. Samples were washed, dried in an oven, weighed, and sieved on a 12-sieve column ranging from 0.5 to 0.063 mm for 20 minutes, in accordance with the AFNOR standard [28].

The results of the granulometric analysis for each sample were presented in the form of frequency curves. The graphical representation adopted in this study follows the model proposed by Besler [5] for classifying dune sands based on their granulometric evolution by utilizing the position and magnitude of their modes. On the x-axis, grain sizes were ordered from finest to coarsest, using an arithmetic scale different from the conventional method employing a logarithmic scale. Two units of measurement were used, millimeters (d) and phi (ϕ), which is defined by Krumbein and Pettijohn [29] as ϕ = –log2(d). The y-axis in the representation differed from the traditional approach by weighting the frequency of each granulometric class by its amplitude, i.e., the difference between the maximum and the minimum sizes of the class in millimeters $\frac{f\,(\%)}{\Delta d\,(mm)}$. This allowed for the derivation of differential frequencies proposed by Besler [5], which adjusted raw frequencies by the size of each class, providing balanced frequencies by individual sizes. This approach proved more suitable for aeolian processes by correcting the emphasis on coarse grains imposed by the arithmetic scale, enabling the distinction and characterization of various granulometric types of aeolian sands [5]. Subsequently, the differential frequencies were normalized to represent density curves in differential frequencies.

To delve further into the analysis and obtain statistically significant results, heterogeneous samples with multiple modes were divided into homogeneous sub-samples. This subdivision was achieved through a simple graphical fractioning of frequency curves, assuming that any heterogeneous grain population consists of homogeneous subpopulations regarding their origin or nature [30].

Classical cumulative curves of populations and homogeneous subpopulations were employed, with a semi-logarithmic representation of the x-axis ordered from coarse to fine grains, to graphically extract percentiles and quartiles. These measures were used for calculating characteristic statistical parameters of granulometric distributions [30, 31], comprising central tendency, dispersion, ranking, and symmetry parameters. These parameters were then utilized for interpreting and inferring transport and sorting modes of the studied sediments.

The graphically derived parameters are presented in phi (ϕ):

- Modal size (Mo): It is the most frequent size and is one indication of the center and homogeneity of the distribution;
- Median size (M): Also known as the 50th percentile (Q2 or ϕ50) dividing the distribution into two equal parts, providing a stable measure of the distribution center most suitable for asymmetrical distributions;
- Quartiles (Q1 and Q3): Correspond to sizes that respectively represent the cumulative frequencies of 25% and 75% on the coarse side of the quartile;
- Percentiles (ϕ5, ϕ16, ϕ84, and ϕ95): Sizes corresponding to cumulative frequencies of 5%, 16%, 84%, and 95% on the coarse side of the percentile.

The calculated parameters [30, 31] include:

- Mean size in ϕ: (1) $\boldsymbol{Mz = \frac{(\phi 16+\phi 50+\phi 84)}{3}}$, providing a representative measure of the distribution center for the quasi-normal and symmetrical distributions;
- Standard deviation in ϕ: (2) $\boldsymbol{\sigma = \frac{(\phi 84-\phi 16)}{4} + \frac{(\phi 95-\phi 5)}{6{,}6}}$, also known as sorting or ranking index, assessing dispersion around the mean and, consequently, the overall grain ranking;
- Kurtosis coefficient (unitless): (3) $\boldsymbol{K_G = \frac{(\phi 95-\phi 5)}{2{,}44(\phi 75-\phi 25)}}$, offering a measure of the distribution shape, whether sharp or flat, by comparing the relative gap in ranking between the curve tail and center; it is very indicative of the aeolian history of dune sands. Leptokurtosis indicates that the sands have been pre-sorted in an earlier aeolian environment, and platykurtosis indicates a mixed deposit, poorly adjusted to the present aeolian environment.
- A mesokurtic curve indicates that older eolian deposits have been reactivated and reworked [5].
- Skewness coefficient (unitless): $\boldsymbol{Sk = \frac{(\phi 16+\phi 84-2\phi 50)}{2(\phi 84-\phi 16)} + \frac{(\phi 5+\phi 95-2\phi 50)}{2(\phi 95-\phi 5)}}$, measuring distribution symmetry by averaging the asymmetry of the 68% of the population centered on the median with those of the 90%.

The skewness of aeolian deposits provides information on the stage of aeolian evolution; if it is seen in combination with the granulometric sand types, for instance, positive skewness increases with aeolian age and is also characteristic of the plinth sand [5].

The interpretation of granulometric parameters aligns with the terminology defined in **Table 1**:

Table 1. Terminology of the granulometric parameters [31].

Storting Index (σ)		Skewness (SK)		Kurtosis (KG)	
<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

The grain size parameters were also used for binary diagrams, whose objectives are the determination of the different types of sand and the identification of possible correlations.

5. Results

5.1. Granulometry and Aeolian Evolution

The approach for granulometric analysis of the oriental sands follows the same methodology adopted for the sands of Merzouga-Tafilalet and Dakhla [26]. Indeed, the frequency graph methodology proposed by Besler [5] was used and explained. Based on this methodology, Besler [5] defined and classified aeolian sands according to the position of their mode and the shape of their distribution, allowing the interpretation of the aeolian evolution of sandy deposits. These sands are derived from alluvial sources, primarily from endorheic rivers, or from other sources such as coastal sands or sands resulting from the weathering of pre-existing rocks, such as granite arenas. The various stages of this aeolian evolution, also referred to as aeolian ages, are described by Besler [5] as follows:

- "Young dune sands" represent the first stage of evolution of the initial sandy deposit, mobilized and cleared of silt-clay dust by deflation. These are composed of the 63–125 µm fraction mobilized by winds inland to form small longitudinal dunes and young barchans.
- The second aeolian age is that of "active crest sands." This stage consists of active dune crests formed after deflation of the very fine sand fraction (63–125 µm) and concentration of the fine fraction (125–250 µm). Active crests are found on primary longitudinal and transverse dunes, on barchans, as well as on secondary dunes of draa after their reactivation. A mixture of the previous two fractions can form "dome sands" by the replenishment of very fine grains.
- The third aeolian age is that of "inactive crest sands," corresponding to the inactivation of dune sands due to the progressive loss of the 125–250 µm fraction, with the 250–500 µm fraction becoming dominant. This stage is found primarily in the lower parts of longitudinal and transverse dunes, as well as on the edges of barchan-type dunes. The preceding simple stages characterize nearly stationary dunes, where only the crest is in permanent movement.
- The fourth aeolian age is that of "old barchan sands," where the 250–500 µm fraction takes precedence over the finer fractions found in the "inactive crest sands." This aeolian evolution characterizes dunes still migrating in the form of barchans. According to Besler [5], the ultimate stage of this aeolian evolution corresponds to a single-mode sand between 250 and 500 µm, representing the final stage in the granulometric evolution of dunes in modern aeolian systems.

Besler [5] has highlighted several possible degenerative stages in this aeolian evolution, occurring when a certain aeolian stability takes over from mobility. "Sand sheet sands" are characterized by a long tail and a reduced mode of residual coarse grains, which can exceed 1000 µm, associated with a modal 63–125 µm fraction that protects it from deflation. "Deflated sands" are bimodal mixtures of a fine fraction trapped because the sandy deposit is no longer mobilized, and a medium fraction. "Plinth sands" are characterized by a flattened plateau from 63 to 500 µm, sometimes with a slight peak in the fines, representing a maximal stability stage where deflation is absent, and all imported fractions are accumulated.

5.2. Classification of Samples

The granulometric analysis of the dune sands in the Oriental region, which are almost devoid of silt-clay fractions (maximum 0.80%), revealed granulometric distributions with five main modes. In the Pelleter's [23] classification triangle, the samples collected from the study site fall almost entirely within the sand field (**Figure 6**).

Figure 6. Classification Triangle after Folk and Ward [31].

5.3. Granulometric Analysis

The granulometrically homogeneous unimodal sands are nearly present for all the samples (**Figure 7**).

The analysis of the very fine grain fraction (S12) with a mode of 112 µm showed an average median size of 150 µm (**Figure 8**). Their average grain size is 150 µm with a mean standard deviation of 36 µm. These are very well-sorted sands, mobilized and deposited by very low-energy winds with minimal fluctuations. The sharpness of their distribution (1.13) is leptokurtic. The skewness coefficient (0.12) is low and skewed toward the finer grains, indicating that their distribution is essentially symmetric, tending toward a slight asymmetry toward the finest grains.

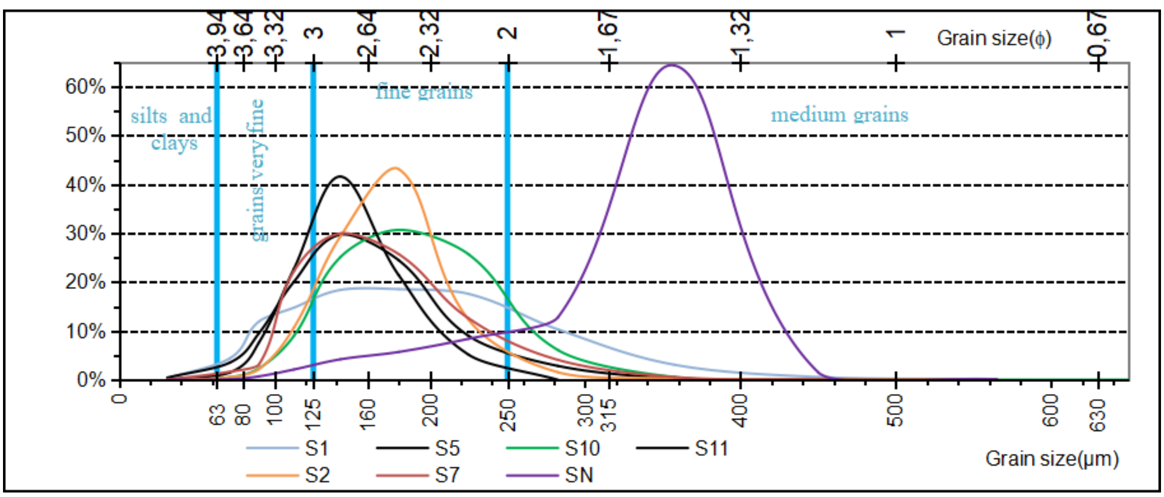

Figure 7. Typical unimodal frequency curves for oriental dune sands.

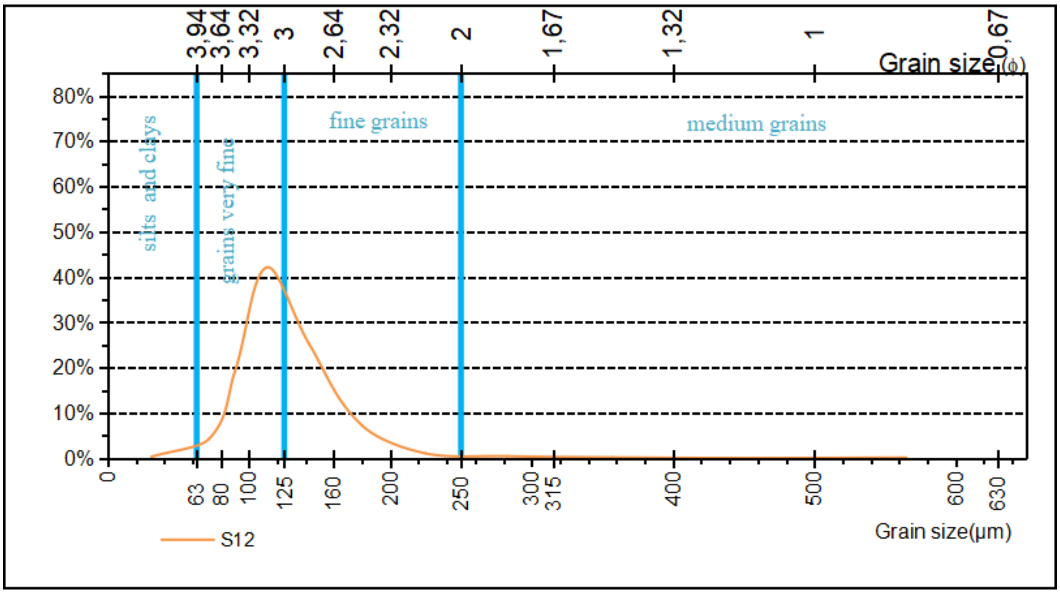

Figure 8. Frequency curve with a mode of 112 µm.

The fine grain fraction, with a mode of 142 µm (S7, S5, Trilobite, S11) (**Figure 9**), showed a median size ranging between 175 and 190 µm, with an average of 182.5 µm. The average grain sizes of these samples range from 168 to 166.42 µm, with an average of 186.3 µm and a mean standard deviation of 56.4 µm. These correspond to well-sorted sands, mobilized and deposited by low-energy winds with minimal fluctuations. Their distribution is leptokurtic to very leptokurtic, with an average sharpness coefficient of 1.44. It is both symmetric and asymmetric, with a weak skew toward the coarse grains and a strong skew toward the finer ones.

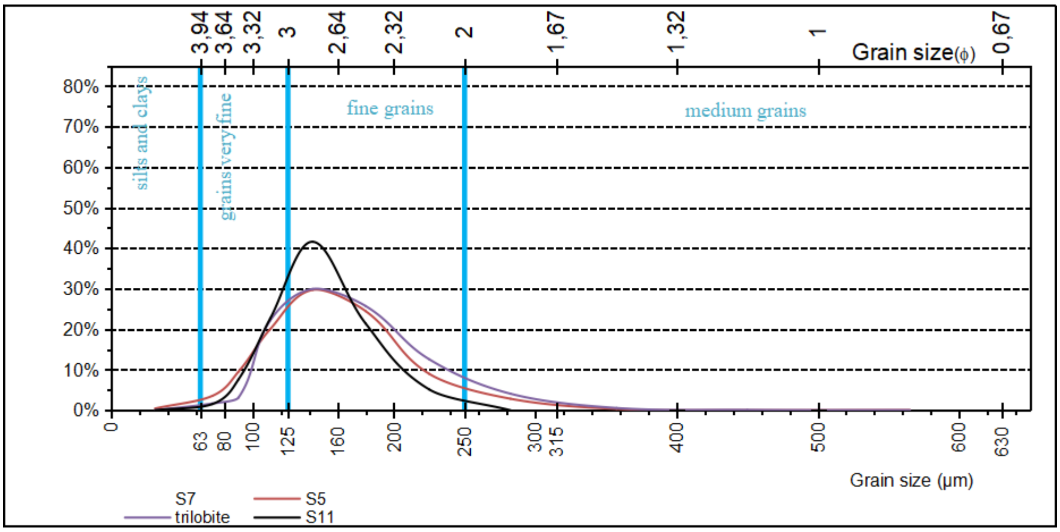

Figure 9. Frequency curve with a mode of 142 µm.

The grains in the fine to medium fraction, with a mode of 180 µm (**Figure 10**), have median sizes ranging from 185 to 195 µm, with an average of 190 µm. Their average grain sizes range from 193 to 195 µm, with an average of 188.8 µm and a mean standard deviation of 41.6 µm. These correspond to very well-sorted sands, mobilized and deposited by winds of low energy, slightly stronger than those responsible for the fine fraction, with minimal fluctuations. Their distribution is leptokurtic, with an average sharpness coefficient of 1.27. It is symmetric range from 193 to 195 µm, with an average of 188.8 µm and a mean standard deviation of 41.6 µm. These correspond to very well-sorted sands, mobilized and deposited by winds of low energy, slightly stronger than those responsible for the fine fraction, with minimal fluctuations. Their distribution is leptokurtic, with an average sharpness coefficient of 1.27. It is symmetric.

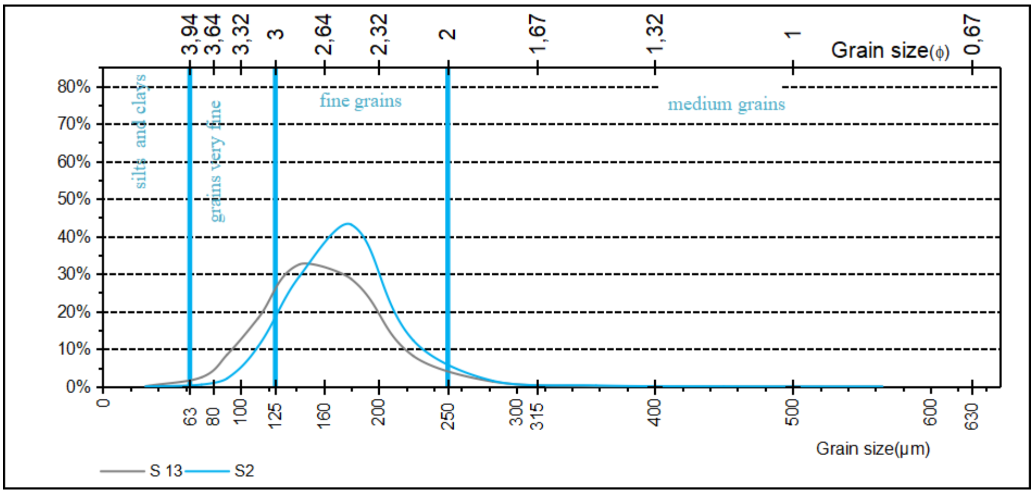

Figure 10. Frequency curve with a mode of 225 µm.

The grains in the fine to medium fraction, with a mode of 225 µm (**Figure 11**), have median sizes ranging from 210 to 220 µm, with an average of 215 µm. Their average grain sizes range from 215 to 217 µm, with an average of 217.1 µm and a mean standard deviation of 83.6 µm. These correspond to well-sorted sands, mobilized and deposited by winds of low energy, slightly stronger than those responsible for the fine fraction, with minimal fluctuations. Their distribution is platykurtic to mesokurtic, with an average sharpness coefficient of 0.89. It is symmetric to weakly asymmetric, both toward the coarser and finer grains.

The grains of the fine to medium fraction, with a mode of 225 µm (**Figure 12**), have median sizes ranging from 210 to 220 µm, with an average of 215 µm. Their average grain sizes range from 215 to 217 µm, with an average of 217.1 µm and a mean standard deviation of 83.6 µm. These grains correspond to well-sorted sands, mobilized and deposited by low-energy winds, slightly stronger than those responsible for the fine fraction, with minimal fluctuations. Their distribution is platykurtic to mesokurtic, with an average sharpness coefficient of 0.89. It is symmetric to weakly asymmetric, both toward the coarser and finer grains.

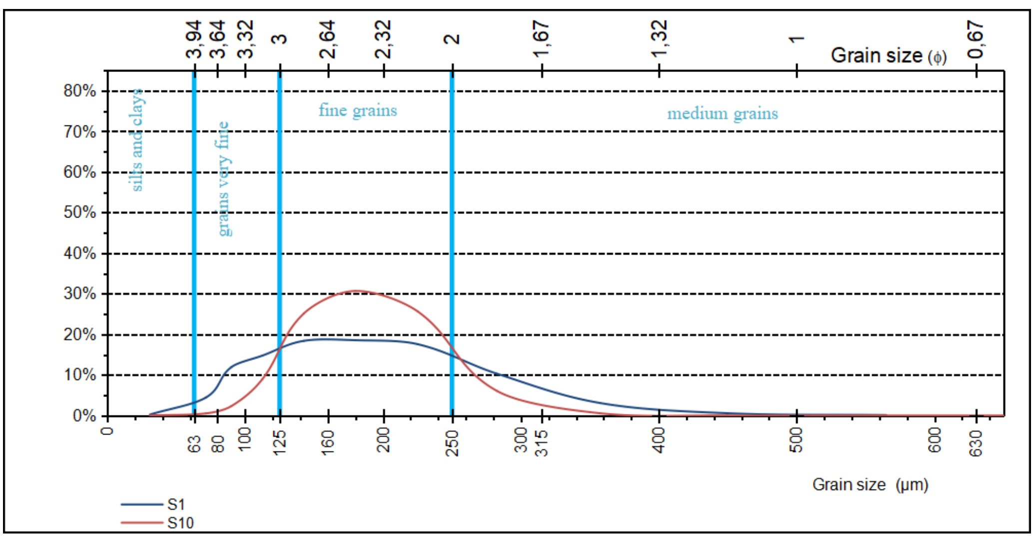

Figure 11. Frequency curve with a mode of 180 µm.

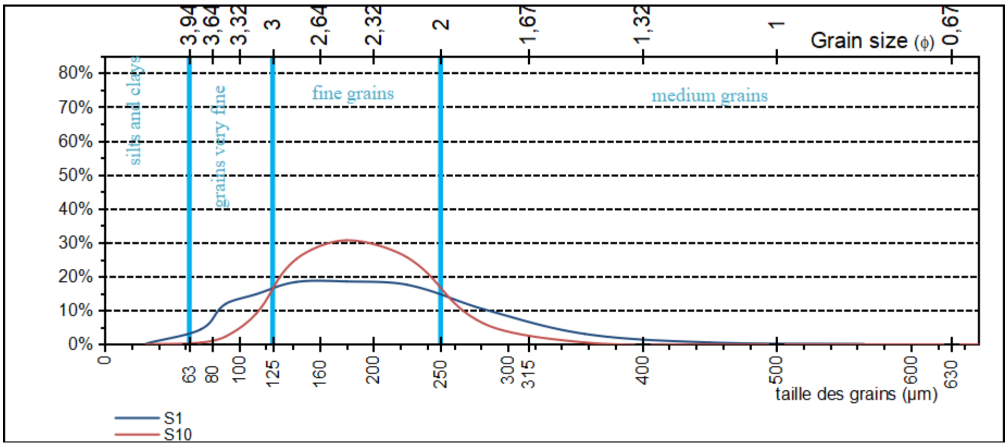

Figure 12. Frequency curve with a mode of 225 µm.

The grains of the medium fraction, with a mode of 357.5 µm (**Figure 13**), have median sizes averaging 185 µm. Their average size ranges from 195.7 µm, with an average standard deviation of 85.7 µm, classifying them as well-sorted sands, mobilized and deposited by winds of low energy, slightly stronger than the fine fraction, with minimal fluctuations. Their distribution is highly leptokurtic, with an average sharpness coefficient of 2.15. It is strongly asymmetric, skewed towards the coarser grains.

The analysis of the frequencies of the homogeneous sandy fractions, derived from the segmentation of initially heterogeneous samples, revealed curves with very sharp peaks for very fine to fine sands, with a very limited medium sand tail and no coarse sand tail, indicating the mobility of the sands in question. Aeolian mobility is a sorting factor responsible for the well-sorted nature of transported and deposited sands, and it is particularly effective when it acts on fine grains[5]. The granulometric evolution interpreted from this analysis also confirmed the mobility of the studied sands, as it is well known that young, active, and inactive dune sands, which make up the majority of the sands in the studied area, are still in motion.

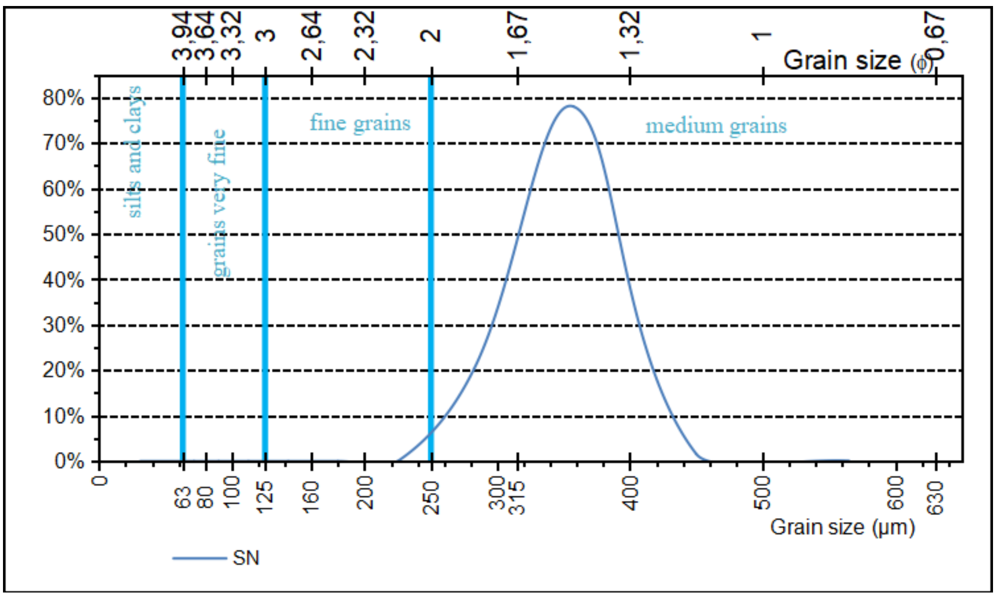

Figure 13. Frequency curve with a mode of 357.5 µm.

To confirm this, the "response diagram" by Besler[32] was used. This diagram, derived from Friedmam's[33] diagram, is used for the quantitative distinction between mobile, stabilized, and residual aeolian sands, as well as fluvial sands.

It is a binary diagram that plots the average Mz in Φ against the sorting index (S0//STDV) in Φ (**Figure 14**).

The mean grain size serves as an indicator of the average kinetic energy of the transport and deposition agent. The sorting index, or standard deviation, represents the variability of this energy around the mean. Since these two parameters can be significantly influenced by sample heterogeneity—resulting from the combination of multiple transport and deposition agents or different grain sources [33]—only the parameters calculated from homogeneous segmented fractions have been plotted on the diagram.

Thus, the response diagram clearly confirms, through their small size and high sorting, that the homogeneous fractions of each sample correspond to aeolian sediments currently undergoing mobilization.

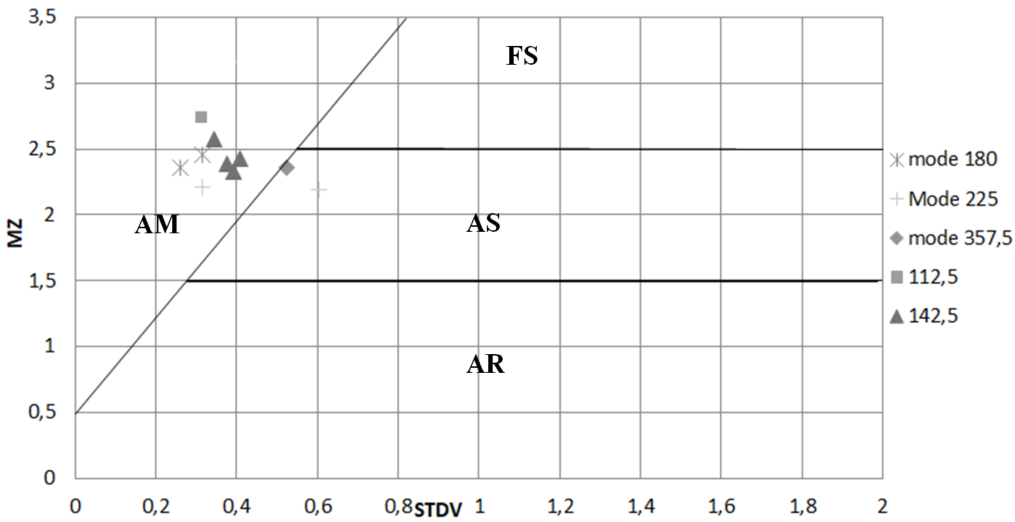

Figure 14. The response diagram [33] of oriental dune sand segments.

Note: Fluvial Sands (FS), Aeolian Mobility Sands (AM), Aeolian Stability Sands (AS), Aeolian Residuals (AR).

5.4. Correlation between Indices and Particle Size Fractions

These correlations between the fractions studied and the granulometric indices (**Figure 15**). In general the mean Mz increases with increasing fraction (the mode); we also note that sorting values become increasingly high as we move to larger modes, implying that poor sorting indicates the onset of mixing of fine, medium and coarse grains with increasingly accentuated aeolian dynamics. As for kurtosis, it rises with the mode values except for fraction 225 µm, which represents an exception. The average asymmetry index shows no correlation with asymmetry, which generally ranges from weak towards fine (fraction 112 µm), symmetrical (fractions 142 µm, 180 µm, and 225 µm) to strong towards coarse (fraction 357 µm).

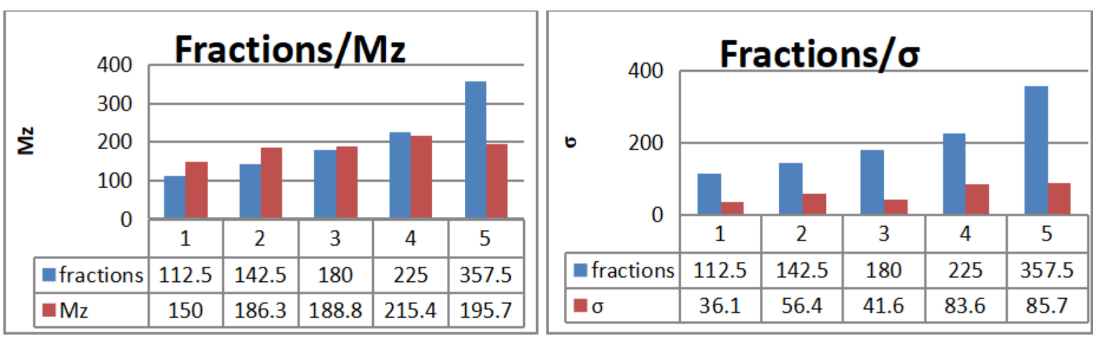

Figure 15. *Cont.*

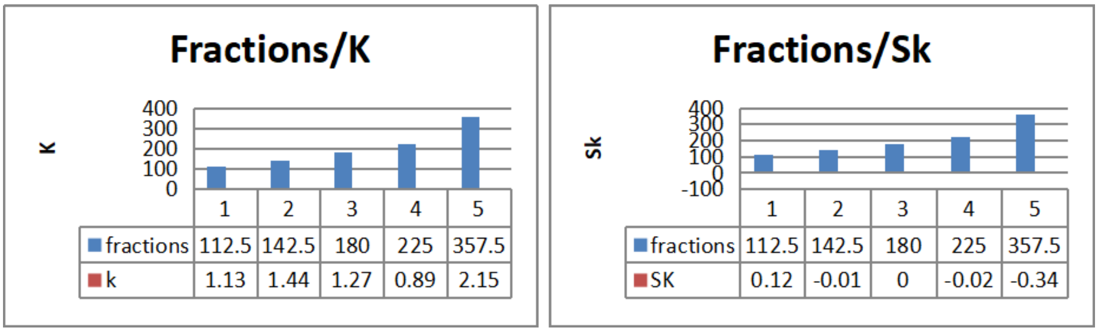

Figure 15. Correlation between particle size fraction and indices (Mz, σ, K, Sk).

6. Discussion

Studies have been carried out on grain-size sand types, based on their characteristic grain-size frequency distributions. Over the years, the concept has been developed and presented as the granulometric evolution of sands [34]. As a valuable source of information on the history of sand seas and dunes, it has been successfully applied to the Libyan desert [35], the Namib erg [36], and, in particular, the Great Sand Sea [37], as well as the Great Sand Sea in Egypt [5]. It has also proved highly instructive on the "Arabian sands" [38]. Aeolian sandstones and Pleistocene inland dunes in Europe [34].

This approach facilitates interpretation and global comparison. In Morocco, this approach to studying the evolution of dune sands was applied to dune sands in the Merzouga-Tafilalet region [26] and to dune sands in the Dakhla region, coupled with mineralogical and geochemical studies. Studies have been carried out on Moroccan dune sands, with different objectives, including those of [39–41], on Merzouga and Tafilalet dune sands from a granulometric, mineralogical and tele-detection point of view. According to Kabiri et al. [39], the absence of any granulometric evolution at Erg Chebbi (Merzouga) indicates that the age of the eolian deposits is older than the barkhane sands responsible for the silting up of the Tafilalet palm groves.

Adnani et al. [42] signaled that than local drainage network is superimposed on the geological formations present in the region. The gullies drain Cretaceous (limestone, marl, clay and conglomeratic sandstone), [43] and Quaternary (travertine, sandstone, sand, red sandy silt, and siliceous and conglomeratic limestone) [44]. Siliceous and conglomeratic [40, 44, 45], in addition to Paleozoic formations (sandstone, shale, conglomerate) [46] reveal that the origin of the sand could also control color variation.

Another study by Adnani et al. [47] The oxidation of sands from the megabarchans of Al-Ghord Lahmar (Khnifiss National Park, South-West of Morocco) under a humid climate is responsible for the reddening of these sands. Besler and Richter [38] studied dune sands from a number of regions, including:

- Dunes along the western base of the Oman mountains in the UAE (Grainage: Mz: 0.1805 mm; So: good to very good; Sk: symmetrical to positive; K: leptokurtic to mesokurtic; Grain age sand types: active ridge sands + inactive ridge sands).
- Dunes in the Al Liwa region and north of it to Abu Dhabi Grainage: Mz: 0.1896 mm; So: mainly good, bad, no, very good; Sk: mainly symmetrical, positive, negative). K: mainly mesokurtic, very platykurtic, leptokurtic; Graded sand types: mainly active ridge sands, inactive ridge sands, megaripple sands.
- Northern dunes of the Wahiba sands in Oman (Grain size: Mz: 0.1663 mm, very homogeneous; So: very good, moderate; Sk: symmetrical, positive; K: mesokurtic, leptokurtic; Grain sand types: mainly active crest sands, dome sands, basement sands).

Regardless of the various transport modes that contributed to the sand stock import into the study area, aeolian dynamics remain the primary agent responsible for their accumulation in the form of dune complexes. This process enabled the segregation of several more or less well-sorted granulometric fractions: very fine (63–100 µm), fine (100–180 µm), and fine to medium (180–350 µm or larger). According to Besler's [32] response diagram, the very fine fraction is characteristic of aeolian mobility, the medium fraction—corresponding to the threshold of movement—lies between aeolian mobility and stability, while the coarser medium fraction, exceeding the mobilization threshold, clearly falls within the stability zone.

Wind evolution in the study area follows three main stages:

Initial sand deposit: This begins with the 112 µm fraction (63–125 µm), resulting from sand mobilization and the removal of fine dust by deflation.

Active ridge sands: These are made up of the 142 µm, 180 µm and 225 µm fractions, resulting from the concentration of fine sand (125–250 µm) after deflation of very fine particles. These active crests appear in various dune shapes (longitudinal, transverse, barchans, reactivated draa). A mixture of the above fractions can form "dome sands".

Inactive crest sands: This stage is marked by the progressive loss of fine fractions (125–250 µm) and the dominance of larger grains (250–500 µm, with a representative fraction of 357 µm). It occurs in the lower parts of dunes and at the edges of barchans, characterizing almost stationary dunes where only the crest remains in motion.

The average for all fractions studied is leptokurtic for fractions 112 µm, 142 µm and 180 µm, indicating that the sands were pre-sorted in an earlier aeolian environment, with a symmetrical curve for the last two fractions typical of active ridge sands and dome sands [38].

As for the 225 µm fraction, it has a platykurtic frequency curve, indicating a mixed deposit, poorly adapted to the current aeolian environment, confirmed by a negative skewness of this fraction reflecting that the sand is not a residue but a poorly adjusted mixture of sands from different sources [38].

The 357 µm fraction shows a very leptokurtic curve, indicating that the sands have been pre-sorted in a previous aeolian environment, with a negative skewness of this fraction reflecting that the sand studied is a poorly adjusted mixture of sands from different sources.

The absence of mesokurtic for all of our samples indicates that none of the aeolian deposits studied were reactivated and reworked after deposition [5].

7. Conclusions

The results of this study highlight the influence of wind dynamics on the particle size distribution of dune sands in the Tandrara-Figuig region. The different fractions identified reveal varied transport and deposition processes under wind regimes of different intensities. The presence of unimodal distributions with fine and coarse tails highlights the alternation between stable and mobile phases of the sands, marking a transition between different aeolian ages.

These observations have major implications for understanding the dynamics of desertification. They show how changing wind regimes influence the formation and transformation of dune landscapes, sometimes promoting erosion and sometimes stabilizing sediments. The progression towards more stable formations, such as sandsheets and plinth sands, reflects a reduction in wind remobilization, which may indicate a change in climatic conditions or sediment supply.

To refine these analyses and better anticipate the impacts of desertification, further research integrating dating, remote sensing, and climate modelling techniques is recommended.

Author Contributions

Conceptualization, methodology, software, and writing, S.H.; conceptualization, methodology, software, and writing, N.A.; visualization, investigation, and reviewing, F.E.H.; reviewing and software, H.T. and A.L. All authors have read and agreed to the published version of the manuscript.

Funding

This work was supported by the Académie Hassan II des Sciences et Techniques (Rabat, Morocco) as part of the AP-2018 project.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The authors agree to share their research data.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] D'Odorico, P., Bhattachan, A., Davis, K.F., et al., 2013. Global desertification: Drivers and feedbacks. Advances in Water Resources. 51, 326–344.

[2] Salvati, L., Sateriano, A., Zitti, M., 2013. Long-term land cover changes and climate variations: A country-scale approach. Environmental Monitoring and Assessment. 185(6), 489–502.

[3] Ladisa, G., Todorovic, M., Liuzzi, G.T., 2014. A GIS-based approach for desertification risk assessment in Apulia region, SE Italy. Physics and Chemistry of the Earth. 49, 103–113.

[4] Belaid, M.A., 2010. Remote sensing of desert cities in developing countries. In: Tarek, R., Carsten, J. (eds.). Remote Sensing of Urban and Suburban Areas. Springer Publisher: New York, NY, USA. pp. 245–265.

[5] Besler, H., 2008. Developments in Sedimentology Series Volume 59: The Great Sand Sea in Egypt. Elsevier Publishing: Amsterdam, The Netherlands.

[6] Karanisa, T., Amato, A., Richer, R., et al., 2021. Agricultural production in Qatar's hot arid climate. Sustainability. 13(7), 4059. DOI: https://doi.org/10.3390/su13074059

[7] Pye, K., Tsoar, H., 2009. Aeolian Sand and Sand Dunes, 2nd ed. Springer: Berlin & Heidelberg, Germany. DOI: https://doi.org/10.1007/978-3-540-85910-9

[8] Sbai, A., Mouadili, O., 2023. Using the GPS station to study wind and coastal morpho-dynamics in Northeastern Morocco. Journal of Geographical Research. 6(1), 28–38. DOI: https://doi.org/10.30564/jgr.v6i1.5270

[9] Bagnold, R.A., 1941. The Physics of Blown Sand and Desert Dunes. Methuen: London, UK. pp. 1–265.

[10] Khalaf, F.I., 1985. Roundness parameters of quartz sand grains of recent aeolian sand deposit in Kuwait. Sedimentary Geology. 45, 137–158.

[11] Teixell, A., Koyi, H.A., 2003. Experimental and field study of the effects of lithological contrasts on thrust-related deformation. Tectonics. 22, 1054–1073.

[12] Michard, A., 1976. Élément de géologie marocaine. Notes et Mémoires du Service Géologique. 252, 408. (in French)

[13] Dresnay, R., 1966. La géomorphologie du Haut Atlas Oriental (Maroc). Quaternaria. 8, 155–165. (in French)

[14] El Kochri, A., Chorowicz, J., 1996. Oblique extension in the Jurassic trough of the central ant easter High Atlas (Morocco). Canadian Journal of Earth Sciences. 33, 84–92.

[15] Houari, M.R., Hoepffner, C., 2000. Structures des terrains paléozoïques à la limite Sud de la chaîne Hercynienne du Maroc (Haut-Atlas Oriental). Africa Geoscience Review. 7(1), 39–53. (in French)

[16] Milhi, A.; El Hmidi, K.; Benaissa, H.; et al., 2010. Mémoire explicatif de la carte géologique du Maroc au 1/50 000; feuille de Jbel Lakhdar Ouest. Report no. 449bis. (in French)

[17] Sharp W.E., 1981. Le gisement d'antimoine d'El Haouanit, région de Bou Arfa, Haut Atlas oriental, Maroc. Report no. 308. (in French)

[18] Baba, E., 1985. Contribution à l'étude lithostratigraphique et structurale des affleurements Paléozoïques de la plaine de Tamlelt au Maroc oriental, et étude par télédétection multispeciale du Haut Atlas oriental [Thèse 3ème Cycle]. Bordeaux, France: Bordeaux I. pp. 1–210. (in French)

[19] Hoepffner, C., 1987. La tectonique hercynienne dans l'Est du Maroc [Thèse d'Etat]. Strasbourg, France: Université de Strasbourg. pp. 1–280. (in French)

[20] Bolata, M., 1995. Étude géologique de la région de Zelmou (Haut atlas oriental, Maroc) [Ph.D. thesis]. Rabat, Morocco: Université Mohammad V. pp. 1–173. (in French)

[21] Khoukhi, Y., 2002. Le paléozoïque inférieur du Haut Atlas Oriental (Maroc): Dynamique sédimentaire, pétrologie et stratigraphie séquentielle [Ph.D. thesis]. Oujda, Morocco: Université Mohamed Premier. pp. 1–302. (in French)

[22] Houari, M.R., 2003. Étude structurale de la boutonnière paléozoïque de Tamlelt (Haut Atlas oriental): Sa place dans la chaîne hercynienne du Maroc [Thèse d'Etat]. Oujda, Morocco: Université Mohamed Premier. pp. 1–353. (in French)

[23] Pelleter, E., 2007. Géologie, géochimie et géochronologie du gisement aurifère de Tamlalt-Menhouhou (Haut Atlas oriental) [Ph.D. thesis]. Nancy, France: Institut National Polytechnique de Lorraine. pp. 1–237. (in French)

[24] Du Dresnay, R., 1976. Carte géologique du Haut Atlas d'Anoual Bouanane au 1/200.000. Report no. 246. (in French)

[25] Bahi, A., Akhssas, A., Ouadif, L., et al., 2018. Contribution of geophysics for the characterization of ore deposits, case of the Bouarfa mine, Morocco. MATEC Web of Conferences. 149, 02076.

[26] Harchane, S., Azzouzi, N., El Hammichi, F., et al., 2024. Merzouga-Tafilalet Sand Dunes (Southeastern Morocco): Sedimentological Study, Mineralogy, Transport Dynamics, and Sand Provenance. Proceedings of The International Conference on Natural Resources and Environment (CIRNE 2023). (in French)

[27] Berthois, L., Le Calez, Y., 1966. Étude sédimentologique des dépôts à « Jullienella fœtida » de la Région d'Abidjan. Bull. du B. R.G.M. 1, 44–55. (in French)

[28] NF EN 933-1. 2018. Essais pour déterminer les caractéristiques Géométriques des granulats – Partie 1: Détermination de la granularité – Analyse granulométrique Par tamisage. (in French)

[29] Krumbein, W.C., Peettijohn, F.J., 1938. Manual of sedimentary petrography. Appleton-Century-Crofts: New York, NY, USA.

[30] Folk, R.L., 1971. Longitudinal dunes of the northwestern edge of the Simpson desert, northern territory, Australia, 1. Geomorphology and grain size relationships. Sedimentology. 16, 5–54.

[31] 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.

[32] Besler, H., 1983. The response diagram: Distinction between aeolian mobility and stability of sands and aeolian residuals by grain size parameters. Zeitschrift für Geomorphologie. Supplementband. 45, 287–301.

[33] Friedman, G.M., 1961. Distinction between dune, beach, and river sands from their textural characteristics. Journal of Sedimentary Research. 31(4), 514–529.

[34] Besler, H., 2005. The granulometric evolution of aeolian sands– an empirical and statistical approach. In: Garcia-Rojo, R., Herrmann, H.J., McNamara, S. (eds.). Powders and Grains. Balkema: Leiden, The Netherlands. pp. 973–976.

[35] Bubenzer, O., Besler, H., 2005. Human occupation of sand seas during the early and mid Holocene, examples from Egypt Zeitschrift fur Geomorphologie, Neue Folge. 138, 153–165.

[36] Bubenzer, O., Bödeker, O., Besler, H., 2007. A transcontinental comparison between the Southern Namib Erg (Namibia) and the southern Great Sand Sea (Egypt). Zentralblatt fur Geologie und Palaontologie. 7–23.

[37] Bubenzer, O., Besler, H., Hilgers, A., 2007. Filling the gap: OSL data expanding ^{14}C chronologies of Late Quaternary environmental change in the Libyan Desert. Quaternary International. 175, 41–52.

[38] Besler, H., Richter, M., 2009. Environmental histories of some Arabian Sands (Oman, United Arab Emirates) deduced from extended sedimentary analysis. Zeitschrift fur Geomorphologie. 53(4), 487–504. DOI: https://doi.org/10.1127/0372-8854/2009/0053-0487

[39] Kabiri, L., Boudad, L., Krimou, A., et al., 2003. Étude préliminaire de la dynamique des dunes Continentales dans le Sud Est marocain. Science et Changement Planétaire / Sécheresse. 14(3), 149–156. (in French)

[40] Boudad, L., Kabiri, L., Weisrock, A., et al., 2003. Les formations fluviatiles du Pléistocène supérieur et de L'Holocène dans la « Plaine » de Tazoughmit (Oued Rheris, piémont sud-atlasique de Goulmima, Maroc). Quaternaire. 14(3), 139–154. (in French)

[41] Benalla, M., Alem, E., Rognon, P., et al., 2003. Les dunes du Tafilalet (Maroc): dynamique éolienne et ensablement des palmeraies. Science et changement planétaire/Sécheresse. 14(2), 73–83. (in French)

[42] Adnani, M., Azzaoui, M.A., Elbelrhiti, H., et al., 2016. Yerdi Sand dunes (Erfoud area, southeastern of Morocco): Color, composition, sand's provenance, and Transport pathways. Arabian Journal of Geosciences. 9, 1–15. DOI: https://doi.org/10.1007/s12517-016-2394-x

[43] Cavin, L., Boudad, L., Duffaud, S., et al. 2001. L'évolution paléoenvironnementale des faunes de poissons du Crétacé supérieur du bassin du Tafilalet et des régions avoisinantes (Sud-Est du Maroc) : implications paléobiogéographiques. Comptes rendus de l'Académie des sciences. Série 2. Sciences de la terre et des planètes, 333(10), 677–683.

[44] Joly, F., Margat, J., 1955. L'évolution récente du réseau hydrographique dans la plaine du Tafilalt (Sud-Est marocain). Notes et Mém. 123, 59–72.

[45] Kabiri, L., Krimou, A., Falguere, C., et al., 2005. Apport des datations radiométriques à la Compréhension de la genèse des carbonates continentaux quaternaires de Yerdi: Significations Paleoclimatiques et paleoenvironnementales (Errachidia, Maroc). (in French)

[46] Michard, A., Saddiqi, O., Chalouan, A., et al., 2008. Continental evolution: The geology of Morocco, Structure, stratigraphy and tectonics of the Africa Atlantic-Mediterranean triple junction. Springer: Berlin, Germany. pp. 1–424.

[47] Adnani, M., Azzaoui, M.A., Elbelrhiti, H., et al., 2018. Investigation of reddening patterns of dune sands—The megabarchans of Al-ghord Lahmar (Khnifiss National Park, South-West of Morocco). Catena. 162, 230–244.