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MINERAL COMPOSITION AND AEOLIAN EVOLUTION OF DUNE DEPOSITS IN MERZOUGA-TAFILALET, SOUTH-EASTERN MOROCCO

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

Geo-resources and Environment laboratory, Sidi Mohammed Ben Abdellah University, Fez, Morocco
e-mail: Smail HARCHANE smailharchane@gmail.com
** corresponding author*

Abstract:
Morocco, like many countries in arid zones, is faced with desertification, particularly in the south and southeast. Shifting dune sand is a key indicator of this phenomenon. The study of aeolian dynamics in the Merzouga-Tafilalet region aims to understand desertification processes, from rock erosion to sediment transport and deposition. A mineralogical and granulometric analysis of dune sand was carried out to determine their composition and origin. The study was based on petrographic examination and identification of the transport mechanisms involved. The sandy deposits are predominantly composed of quartz, with the presence of oxides, heavy minerals, feldspars, micas and calcite. These elements originate from the crystalline formations of the Anti-Atlas and are transported by aeolian and hydrological processes. Analysis of the quartz grains reveals different morphologies, reflecting the history of their transport and deposition. Aeolian dynamics have led to the formation of distinct granulometric fractions, each corresponding to a specific aeolian period. The mixing of these fractions results from the alternation of strong and weak wind regimes, as well as stabilization phases linked to wind degeneration. This study provides a better understanding of the evolution of dune sand in the face of environmental change.

Key-words: Desertification; wind dynamics; dune sand,; aeolian evolution; mineral composition, South-Eastern Morocco.

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INTRODUCTION

The southeastern regions of Morocco are currently experiencing alarming land degradation, accompanied by disturbances affecting biological resources and land potential. The emergence and natural evolution of aeolian desertification is a recurrent phenomenon in semi-arid environments, particularly in this part of the Moroccan territory. Aeolian erosion and the advance of mobile dunes pose a significant threat to oases and fluvial terraces, leading to the gradual destruction of vegetal cover. Sand accumulations in this region are characterized by dunes reaching heights of up to four meters, as well as dune ridges that traverse palm groves in the form of fine deposits a few centimetres thick. The dynamics of these formations are primarily governed by two dominant wind directions: one originating from the southwest and the other from the northeast. According to estimates by Ilmen and Benjelloun (2013), the average dune migration rate ranges between 10 and 15 m per year. The extent of this phenomenon has significantly increased over the past decades due to declining precipitation and intensified evapotranspiration.SE

This study aims to enhance the understanding of dune dynamics in southeastern Morocco by analyzing the dune sand of this region and presenting the results of granulometric and mineralogical investigations conducted on samples collected from the Merzouga-Tafilalet area. The granulometric analysis seeks to characterize the distribution of sand deposits, identify different granular fractions and their associations, and reconstruct the aeolian dynamics responsible for the transport, segregation, and deposition of sandy materials. The mineralogical and petrographic study focuses on a morphoscopic analysis of quartz grains, the main constituent of the deposits studied, in order to elucidate the transport mechanisms shaping these accumulations as well as the mineralogy of heavy and light minerals. In addition, it aims to identify the composition of non-quartz mineral phases, as well as the mineralogy of heavy and light minerals, in order to highlight potential correlations for tracing the lithological origin of the dune materials.

GEOMORPHOLOGICAL, CLIMATIC AND GEOLOGICAL SETTING

The study area is located in the extreme southeast of Morocco, a region characterized by diverse topography, including plains, plateaus, and ancient massifs (Fig. 1). It is bordered by a vast piedmont plateau, shaped by the partial erosion of the sedimentary cover overlying the ancient South Moroccan basement. The area encompasses the Tafilelt Plain, the adjacent Maider Plateau, and parts of the Guir Hamada to the east and southeast, as well as the Kem-Kem Hamada to the south. It is bounded to the northwest by the Precambrian and Palaeozoic massifs of Saghro and Ougnate, to the north by the Cretaceous and Tertiary basins of Errachidia-Boudnib and Ouarzazate, and to the west by the Tazarine depression. The Tafilelt Plain is a broad depression traversed by the Ziz River, while the Maider Plateau exhibits a rugged and difficult-to-access relief. Both Tafilelt and Maider consist of Palaeozoic terrains deformed during the Hercynian orogeny. The hamadas, on the other hand, are characterized by vast plateaus dissected by steep cliffs and ephemeral drainage networks.

The arid climate favors intense aeolian processes that play a crucial role in shaping today's landscape. The strong wind that sweeps across the Tafilelt plain mobilize fine sediments from desert formations and redistribute them in vast dune fields in contact with Paleozoic reliefs. Average highs in the hottest month can reach 42.6°C, while lows in the coldest month are around -1.8°C. Precipitation averages around 90.47 mm/year, but is infrequent and irregular, obviously due to the region's geographical position, far from any oceanic influence, and its openness to the warm air masses of the Sahara (Mina, 1991). The wind in the region is classified as medium to strong breeze (Beaufort scale), with speeds often varying between 1 and 5 m/s, with a calculated average of 2.9 m/s, giving it a high ranking.

Erg Chebbi, east of Tafilelt near Merzouga, is the most emblematic sand accumulation. The dunes of this erg present a variety of morphologies, reflecting the multidirectional nature of the prevailing winds (Alali and Benmohammadi, 2013). Their evolution is influenced by wind speed and gust frequency, leading to migration and the formation of new structures.

The regional stratigraphic formations range from the Precambrian to the Quaternary (Fig. 1). Palaeozoic terrains, affected by the Hercynian orogeny, overlay the Precambrian axial zone of the Anti-Atlas in large anticlinal and synclinal structures. The Mesozoic and Cenozoic cover consists of continental and marine sedimentary deposits, particularly the Cretaceous and Tertiary tabular formations of the hamadas. The Quaternary is marked by diverse deposits, recording past climatic fluctuations through alternating pluvial and interpluvial periods (Choubert and Faure-Muret, 1965; Joly, 1962).

All stages of Morocco's continental Quaternary stratigraphy have been identified in this region (Destombes and Hollard, 1986). Thus, the present-day landscape of southeastern Morocco results from a complex interplay of tectonic, climatic, and aeolian dynamics. The presence of extensive dune fields and Quaternary formations illustrates the recent evolution of this Saharan region, where wind action continuously sculpts the relief. Among these, the Erg Chebbi, located east of Tafilelt near Merzouga, is the most iconic sand accumulation. The dunes within this erg ex-

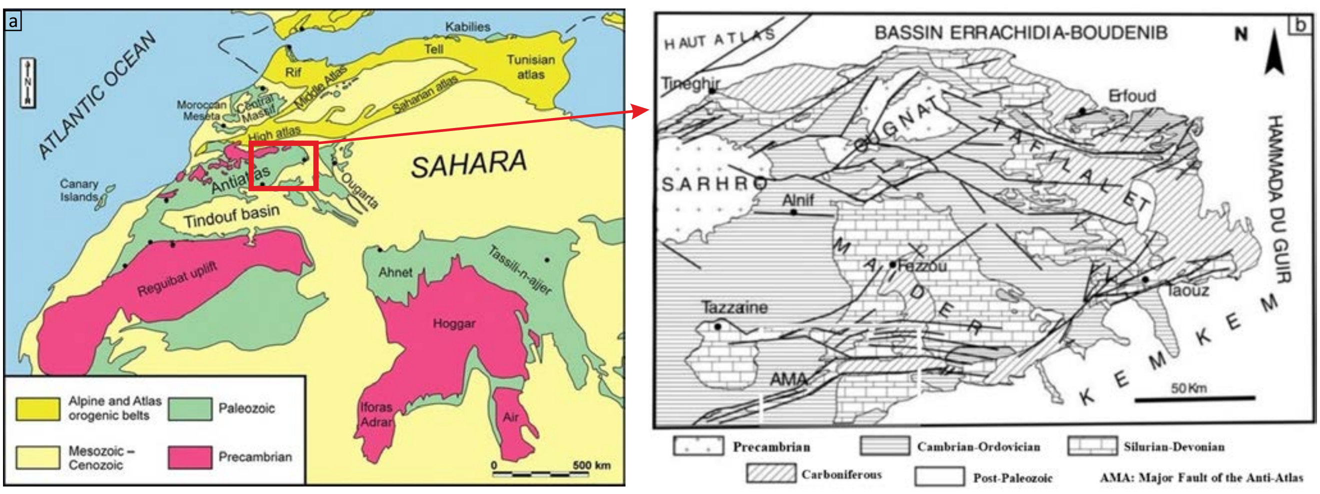


Fig. 1. (a) Simplified geological map of Northwestern Africa with location of studied area (modified from Julivert, 2003). the red square represents the study area ; (b) Structural map based on (Baidder, 2007).

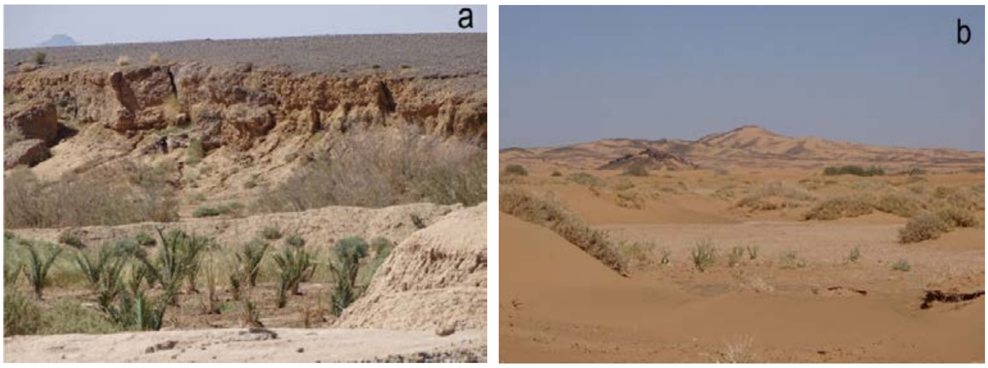


Fig. 2. (a) Heavily encrusted terraces on the bank of the Oued Ziz, (b) Accumulation of mobile sand to the west of the Ziz valley (bordering the Taouz region).

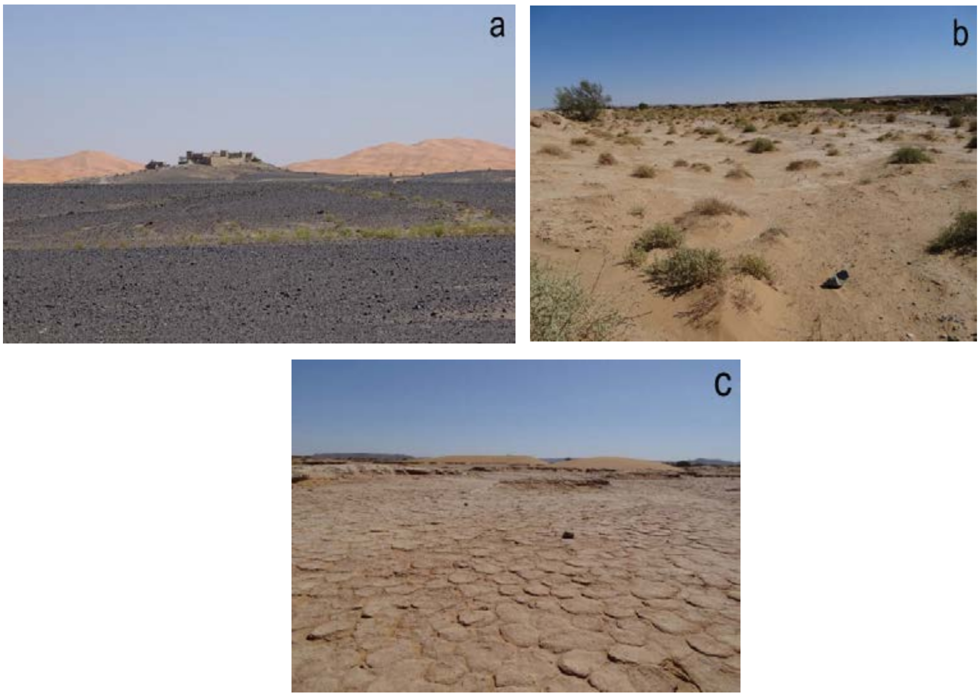


Fig. 3. (a) Erg of Merzouga at the bottom of the image with the Visean alternating shales and fine sandstones near the village of Merzouga, N-S view, (b) Sandy accumulation limited by vegetation, (c) Saline soils on the edge of sandy accumulations (Oued Begga NE of Taouz).

hibit diverse morphologies, reflecting the multidirectional nature of dominant wind. Their evolution is influenced by wind velocity and gust frequency, driving their migration and the formation of new structures (Adnani *et al*., 2016).

The dunes are of two types: classic dunes with well-defined shapes, classified according to wind dynamics, in the form of barkhanes to the south and south-east of the Jorf, Hannabou and Rissani palm groves, and barkhanoid cordons along the Oued Rhéris to the north of Hannabou, the linear dunes (Aklés) that mark the Yerdi area and finally the star or pyramidal dunes of Merzouga and complex dunes whose forms are massive accumulations such as ergs or large-scale dune edifices essentially mark the Magha region to the east of Tafilalet and Yerdi to the west. These areas, characterized by aklés-type dunes, are at the start of erg formation (Benalla *et al*., 2003).

Dunes primarily develop along NW-SE-oriented corridors, linked to the Ziz Valley. They occasionally cover sebkhas, halomorphic soils, and vegetated areas, continuously reshaping the landscape (Figs 2 and 3). Some dunes remain stabilized by sparse vegetation, while others remain mobile, contributing to the encroachment of certain areas.

MATERIALS AND METHODS

A sampling campaign was carried out on sand accumulations in the Merzouga-Tafilelt, Bouanane, M'hamid, Zagora and Boudnib regions. At the same time, a geological study of the surrounding formations was carried out. Surface samples (Fig. 4), were stored in labelled plastic bags and assigned to particle size determination, morphoscopic analysis and geochemical study. Sampling sites were geolocated using GPS (Fig. 5).

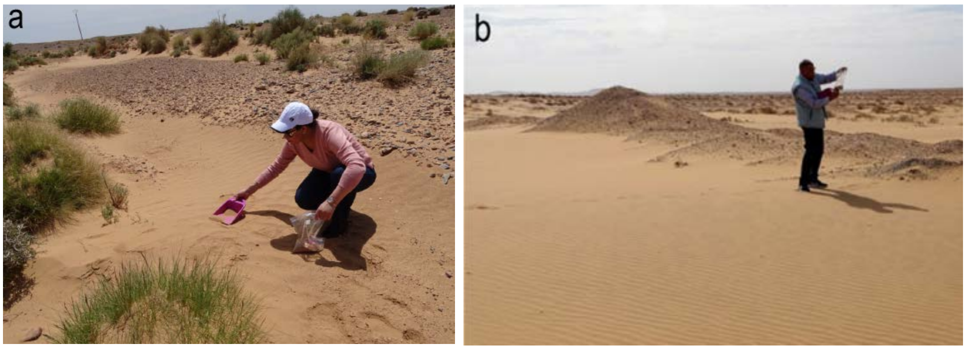


Fig. 4. Sampling of sand moving in the direction of wind currents in the region: (a) d'Ain Chouater (Bouanane region) and (b) east of Merzouga.

Grain size distribution analysis

Granulometric analysis was performed using the traditional method described by (Berthois and Le Calez, 1966), where samples were washed, dried, weighed, and sieved through a column of 12 sieves (ranging from 0.5 to 0.063 mm) for 20 minutes, following AFNOR standards (2018). The results were presented as frequency curves. The study adopted Besler's (2008) method for classifying dune sand based on granulometric evolution. The x-axis represented grain sizes from finest to coarsest in an arithmetic scale, while the y-axis accounted for the frequency of each size class, adjusted by its amplitude (f (%)/φd (mm)). This approach corrected the bias towards coarse grains typical of the arithmetic scale, allowing for a clearer distinction of various aeolian sand types. The differential frequencies were normalized into density curves.

To go further in the analysis and obtain significant statistical results, the heterogeneous samples with multiple modes were split into homogeneous sub-samples, on the basis on the hypothesis that any heterogeneous population of grains is composed of sub-populations homogeneous in terms of their origin or nature (Folk, 1971). The method employed is a simple graphical splitting of the frequency curves. It consists of smoothing and tracing the continuity of the descending slopes between two modes while preserving their curvature. The intersection of these newly drawn curves constitutes the cutoff threshold between the two resulting subpopulations. The advantage of this method lies in its ability to naturally refine the separation of mixed populations while maintaining the initial morphology of the mixture's distribution. Moreover, it allows for a more representative adjustment of the cutoff threshold, reflecting the actual contribution of each subpopulation more accurately than the minimum of the initial curve. The choice of this approach over a more statistically rigorous method was facilitated by the limited number of samples and the near absence of noise, and was primarily driven by our intent to preserve the original morphology of the unmixed components.

Given that the parameters derived from the statistical analysis of any heterogeneous population are neither significant nor representative, it was decided to apply such an analysis only to the previously segmented fractions. The classical cumulative curves of both the homogeneous populations and the subpopulations were employed for the graphical extraction of the mode, median and percentiles. These values were then used to calculate the statistical parameters characteristic of granulometric distributions (Folk and Ward, 1957; Folk, 1971). Accordingly, granulometric indices of central tendency, dispersion, sorting, and skewness were determined to facilitate interpretations and deductions regarding the transport and sorting mechanisms of the studied sediments. Additionally, Besler's (1983) response diagram, modified from Friedman (1961), which plots the mean grain size against the sorting index, was plotted.

The morphoscopy and mineralogy composition analysis

Morphoscopic analysis was conducted using a Binocular magnifier (x100). Observed criteria are color, and shape (Parfenoff *et al.*, 1970). Counting was performed on approximately one hundred grains, examining each mode representative of each sample. Heavy minerals were separated using bromoform prior to observation to facilitate their mineralogical determination. Grain morphoscopy aims to obtain a statistical determination of the petrographic and mineralogical composition and the proportions of the grains constituting the sand deposits (Le Ribault, 1977). Determining the shape and aspect of detrital quartz grains allowed for the interpretation of their modes of transport. Petrographic description of non-quartz grains enabled the identification of their mineralogy and interpretation of their origin.

In addition to petrographic observation, X-ray diffractometry was used to qualitatively determine the mineralogical composition of the constituent grains of the studied sand. A portion of dried raw sand was ground and analyzed using an X-ray diffractometer (XRD). Chemical constituents were identified through peaks corresponding to their 2θ values.

Calcimetry was employed to assess the carbonate content of the sediments. This analysis is based on the measurement of the volume of carbon dioxide released by a known quantity of sediments reacting with hydrochloric acid.

Statistical analysis of multidimensional correlations was performed using principal component analysis (PCA) to identify possible correlations between different petro-

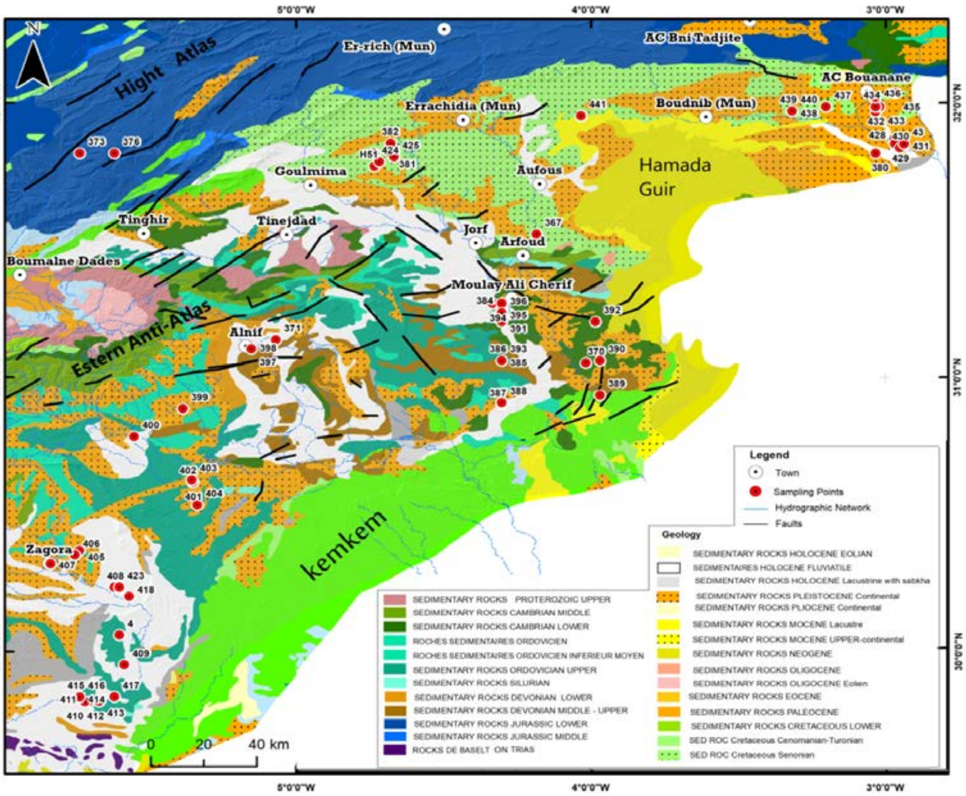


Fig. 5. (a) Position of Tafilelt and Maider in the structural domain in the eastern Anti-Atlas; (b) Sampling sites for sedimentological analyses of SE Morocco: Ressani-Merzouga (367 to 384), Tazarine-Alnif (385 to 392), Taghbalt (393), Zgoura-M'hamid lghzlane (394 to 413), Erachidia (415 to 418), Boudnib (436 to 442), Bouanane (423 to 435).

graphic and mineralogical components of Merzouga-Tafilelt dune sand.

RESULTS

Grain Size Distribution

Preliminary particle size analysis of Merzouga-Tafilelt dune sand revealed variations in distribution. Unimodal sand is rare, represented by the samples 386, 431, 378 and 435. Most of the sand analyzed shows heterogeneous, bimodal or trimodal particle size distributions (Fig. 6), with distinct modes, either diffuse or integrated into a platykurtic curve modes. These modes generally occupy well-defined and relatively stable positions: the first mode is moving between 70 and 112 µm, the second one is around 142 µm, and the last one is around 225 µm. They thus represent three distinct grain fractions: very fine (63–125 µm), fine (100–220 µm) and fine to medium ones (180–315 µm). A reduced tail extending up to 500 µm is added to the main modal fractions. Additionally, the silty-clay fraction is almost absent or very minor (0.01–2.25%).

The analysis following segmentation revealed that the very fine fraction has a median size ranging between 90 and 114 µm, with an average of 102.6 µm. Their mean size varies from 91.7 to 111.2 µm, averaging 102.5 µm, with a standard deviation of 21 µm in average, indicating excellent sorting. The skewness coefficient of such sand indicates that their distribution is predominantly symmetric, with a slight tendency to fine skewness. The fine grain fraction has a median size ranging from 147 to 165 µm, with an average of 155 µm. The mean size of these grains range from 138.6 to 166.4 µm, with an average of 152.3 µm and a standard deviation of 33 µm in average. This characterizes them as very well-sorted sand. The distribution is mesokurtic to leptokurtic, with an average sharpness coefficient of 1.14. It can be symmetrical to asymmetrical, with a skewness ranging from coarse to strongly fine. The grains of the fine to medium fraction have median size ranging from 220 to 255 µm, with an average of 242 µm. Their mean sizes range from 212 to 261.6 µm, with an average of 240 µm and a standard deviation of 38 µm in average. This fraction also corresponds to very well-sorted sand. The distribution is platykurtic, mesokurtic to leptokurtic, with an average sharpness coefficient of 1.04. It can be symmetrical to weakly asymmetrical towards both larger grains and finer grains.

Three main configurations of dune sand stocks were observed in the study area: a unimodal configuration and two mixed configurations featuring two or three more or less distinct modes. These modes, while varying in relative importance, maintained a fairly stable position.

1. The unimodal, granulometrically homogeneous sand (Fig. 7) is fairly well sorted, with a narrow standard deviation ranging between 35 and 80 µm. The distribution varies from leptokurtic to mesokurtic, with an average kurtosis

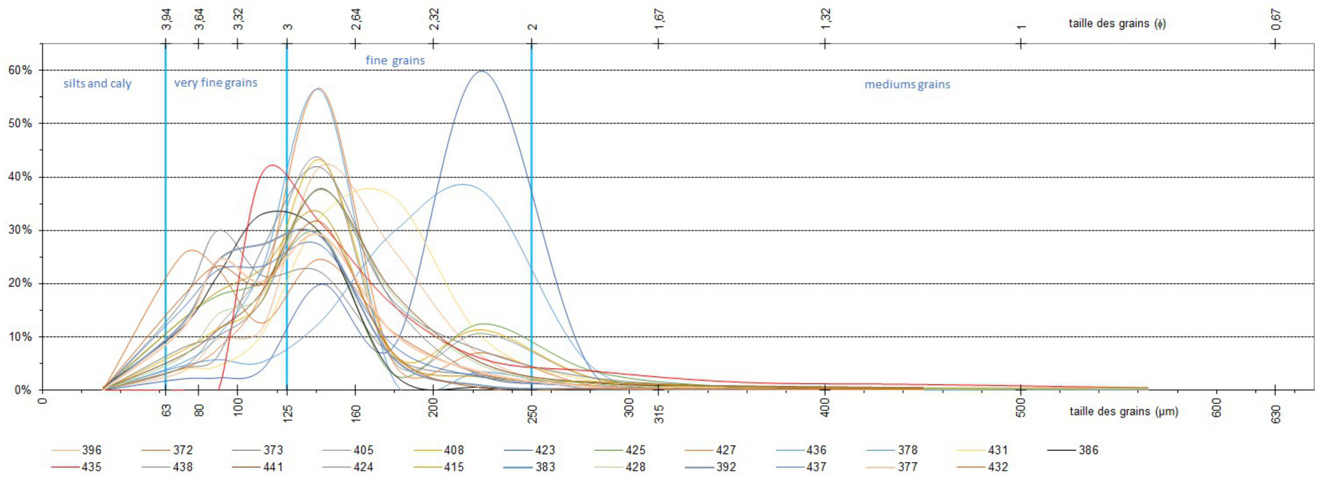


Fig. 6. Typical granulometric frequency curves for Merzouga-Tafilelt dune sand.

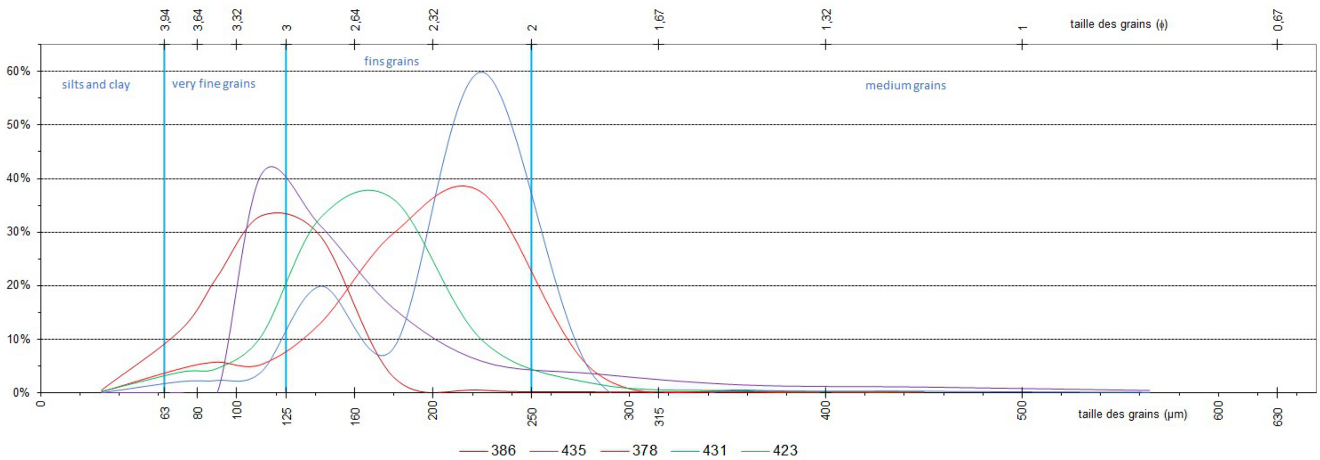


Fig. 7. The unimodal distribution configuration of Merzouga-Tafilelt dune sand.

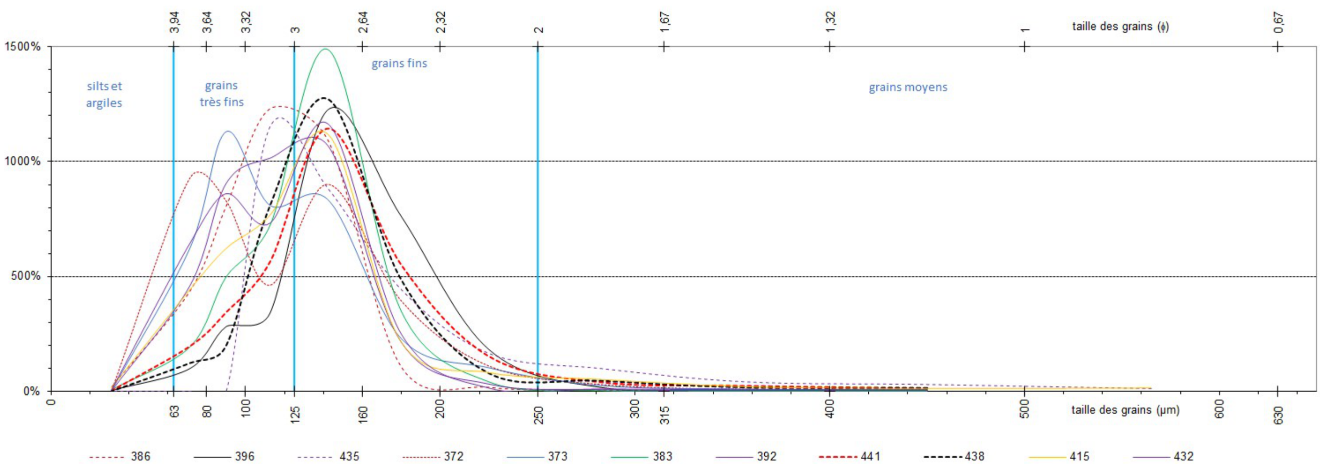


Fig. 8. The two-mode distribution configuration of Merzouga-Tafilelt dune sand.

coefficient of 1.15. The four representative samples (Fig. 8) exhibit the following specific characteristics:

- Sample 386: a broad-mode distribution composed of two granulometric classes (100 to 160 µm), with very fine and fine fractions present in equal proportions.
- Sample 431: a broad-mode distribution comprising two granulometric classes (125 to 200 µm), where the very fine fraction is highly minor and lacks a distinct mode, the fine fraction is predominant, and a reduced tail of the fine-to-medium fraction is present.

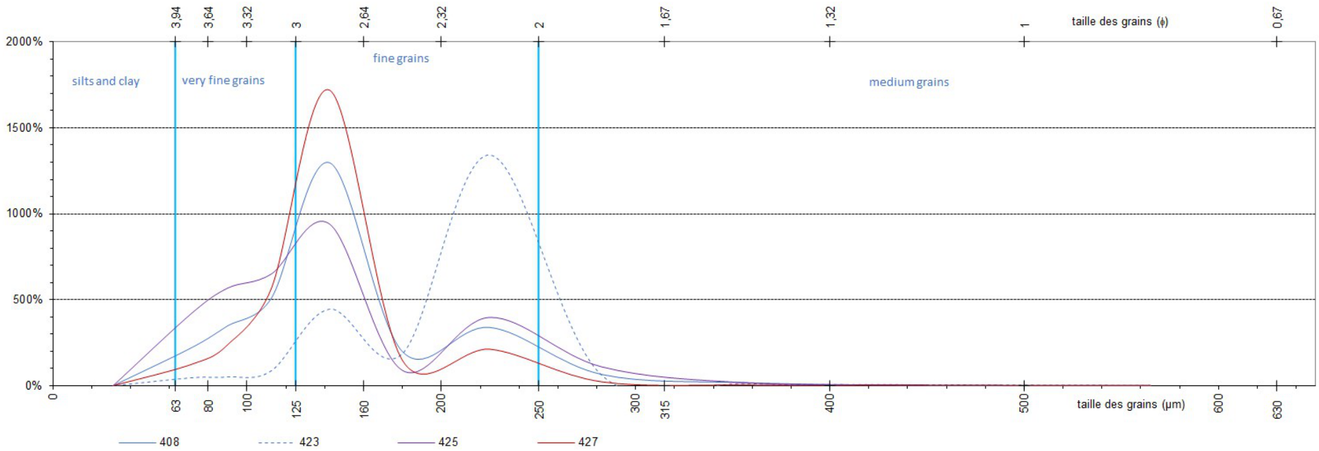


Fig. 9. The three-mode distribution configuration of Merzouga-Tafilelt dune sand.

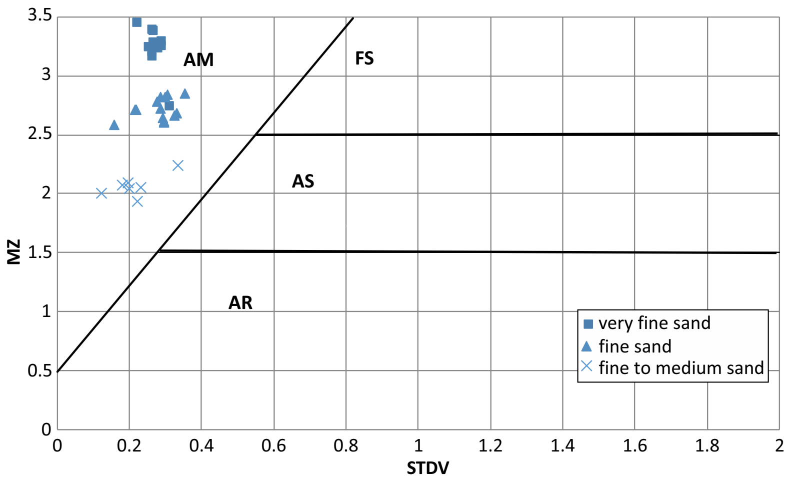


Fig. 10. The response diagram (Besler, 1983) of Merzouga-Tafilelt dune segments of sand: fluvial sand (FS), aeolian mobility sand (AM), aeolian stability sand (AS) and aeolian residuals (AR).

- Sample 378: a broad-mode distribution consisting of two granulometric classes (180 to 240 μm), where the very fine fraction is highly minor, the fine fraction is reduced, and the fine-to-medium fraction is dominant.
- Sample 435: an individualized-mode distribution (at 115 μm), characterized by a dominant very fine fraction (90 to 125 μm), an intermediate fine fraction, and an extended but reduced fine-to-medium fraction, displaying strong asymmetry toward coarser grains.

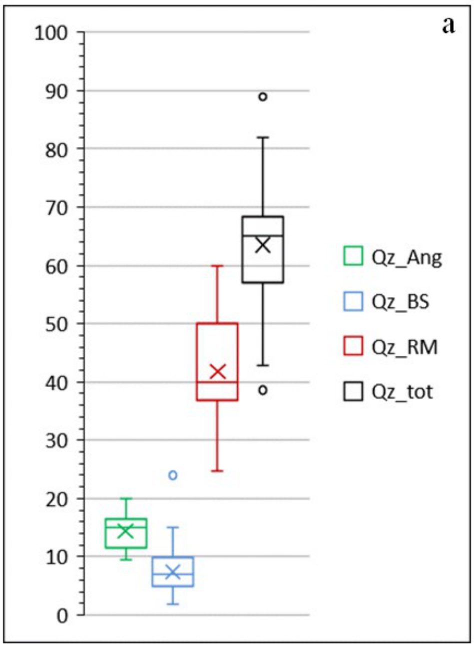
2. The bimodal distribution (Fig. 8): This distribution features a dominant mode, often corresponding to the 100–220 μm fraction, and a reduced mode, typically within the 63–125 μm fraction, accompanied by a flat tail extending from 220 to 500 μm. The two modes are more or less fused.

3. The three-mode distribution (Fig. 9): it consists of a dominant mode (100–220 μm fraction), a reduced mode fused to the dominant mode (63–125 μm fraction), a distinct reduced mode (180–315 μm fraction), and a flat tail extending from 315 to 500 μm. A variant of this distribution was observed in a single sample (Sample 423). It is bimodal with the very fine fraction having almost disappeared, the fine fraction having regressed and the fine-to-medium fraction has become predominant.

The response diagram of (Besler, 1983) was used for the quantitative distinction between mobile, stabilized and residual aeolian sand, as well as fluvial sand (Fig. 10). The mean size is 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. The three particle size fractions related to the Merzouga-Tafilelt sand stocks were positioned in the aeolian mobility.

Morphoscopy and mineralogy

Binocular magnifier observation of dune sand from Merzouga-Tafilelt showed that they are predominantly composed of quartz grains (Fig. 11a), representing on average two-thirds, with a minimum of 40% and a maximum of 90%. This observation was confirmed by X-ray diffraction, showing predominant peaks for silica. Morphoscopic analysis of quartz grains revealed that they are primarily round and mat. However, blunt and shiny grains and angular grains were also found, along with a few grains slightly colored by ferruginous patinas. Among quartz grains



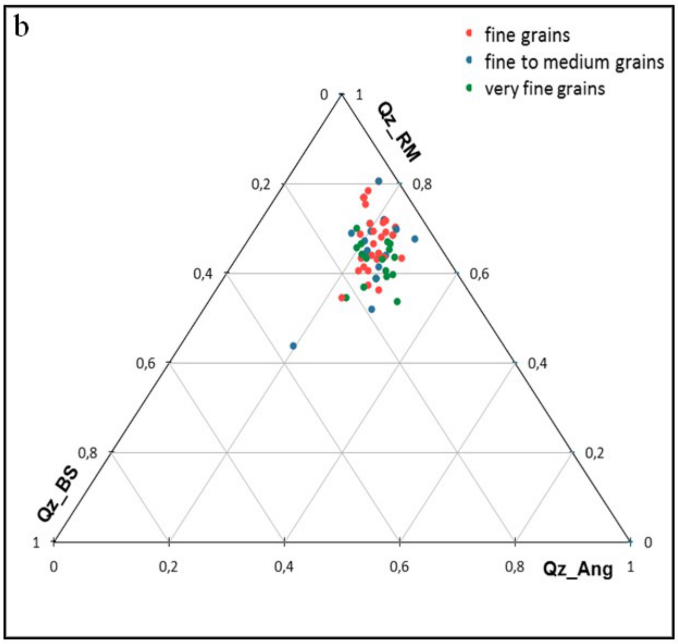


Fig. 11. (a) Proportions of quartz and its three forms within the sandy stocks of Merzouga-Tafilelt dunes. (b) Relative proportions of the three forms of quartz within the quartz stock of the sand of Merzouga-Tafilelt dunes. Qz_Ang – angular quartz grains, Qz_RM – round mat quartz grains, Qz_BS – blunt shiny quartz grains, Qz_tot – total quartz grains

(Fig. 11b), the proportions averaged 66% for round and mat grains (ranging from 52% to 80%), 23% for angular grains on average (from 15% to 32%), and 12% for blunt shiny grains on average (from 3% to 23%).

Heavy minerals are substantial components of sand in the study area (Fig. 12a), and are of great interest to our study, since they provide information on the potential sources of dune deposits, averaging 20% of the grains, with a maximum of 40%. Observed heavy minerals include epidote, averaging 4.3% of the whole stock of sand (Fig. 12a) and 22.5% of heavy minerals, garnet (4% and 21%), tourmaline (3.5% and 17.2%), rutile (2.9% and 15.5%), staurolite (1.7% and 8.5%), zircon (1.7% and 9%), and kyanite (1.3% and 7%) (Fig. 12a). The alumina content detected by XRD is significant (20%), primarily originating from silicates such as feldspars, micas, and heavy minerals. Oxides are present in significant quantities as grains (Fig. 12b), averaging 7% of the grains, with a maximum of 16%. They mainly consist of magnetite, ilmenite, and other oxides, with their respective average proportions (Fig. 12b) and (Fig. 12c) being 38%, 35%, and 26%, with a nearly balanced distribution. The diffraction peaks of oxides confirmed these observations. Feldspars are present in minority (Fig. 13c), averaging 3% of the grains, with a maximum of 7%. Micas are very rare (Fig. 12d) , constituting less than 1% of the grains on average and reaching a maximum of 5%. Rock fragments of various colors: bright green, brown, whitish, yellowish and grayish, difficult to determine, are present in significant proportion, averaging 3.8% of the grains, with a maximum of 11% (Fig. 12e). Observed limestone grains appear in two forms: shell fragments of biodetritic origin, present in very few samples, and chemical calcite flakes, present in half of the samples but in very minor proportions (Fig. 12e).

Principal Component Analysis (PCA) identified some correlations (Fig. 13) between petrographic and mineralogical components of Merzouga-Tafilelt dune sand. However, only about 50% of the total variability was described with the three principal factors selected for this presentation: this is of average quality due to the weak variability and the small number of observations. The eigenvalues of each component are provided in the variable plots (Fig. 13). The contributions of each variable to the principal components, expressed as percentages, and the proportion of the variance explained for each variable by the principal components ($\cos^2$) are presented in (Table 1).

Quartz, in its three forms, is negatively correlated with all other components on factor F1 (Fig. 13a and b), except for kyanite, rock fragments, and biodetritic calcite. The factorial planes F1-F2-F3 show that angular quartz grains are weakly correlated with shiny blunt grains. Mat round grains are not correlated with shiny blunt grains or angular grains. The three different forms of quartz are not correlated with grain sizes (Fig. 11b). Their distributions within each modal fraction are similar.

The factorial plane F1-F2 (Fig. 13a) highlights three groups of positive correlations: different quartz on one hand, plagioclases, micas, oxides, garnet, and chemical calcite opposed to quartz on the other hand, and finally, zircon, rutile, epidote, staurolite, kyanite, and tourmaline, not correlated with the other two groups. The factorial plane F1-F3 (Fig. 13b) highlights the positive correlation between oxides, garnet, staurolite, tourmaline, and plagioclase. The factorial plane F2-F3 (Fig. 13c) highlights the positive correlation between kyanite and zircon and their opposition to micas and plagioclases. The positive correlation between shiny blunt and angular quartz with potassium feldspar is

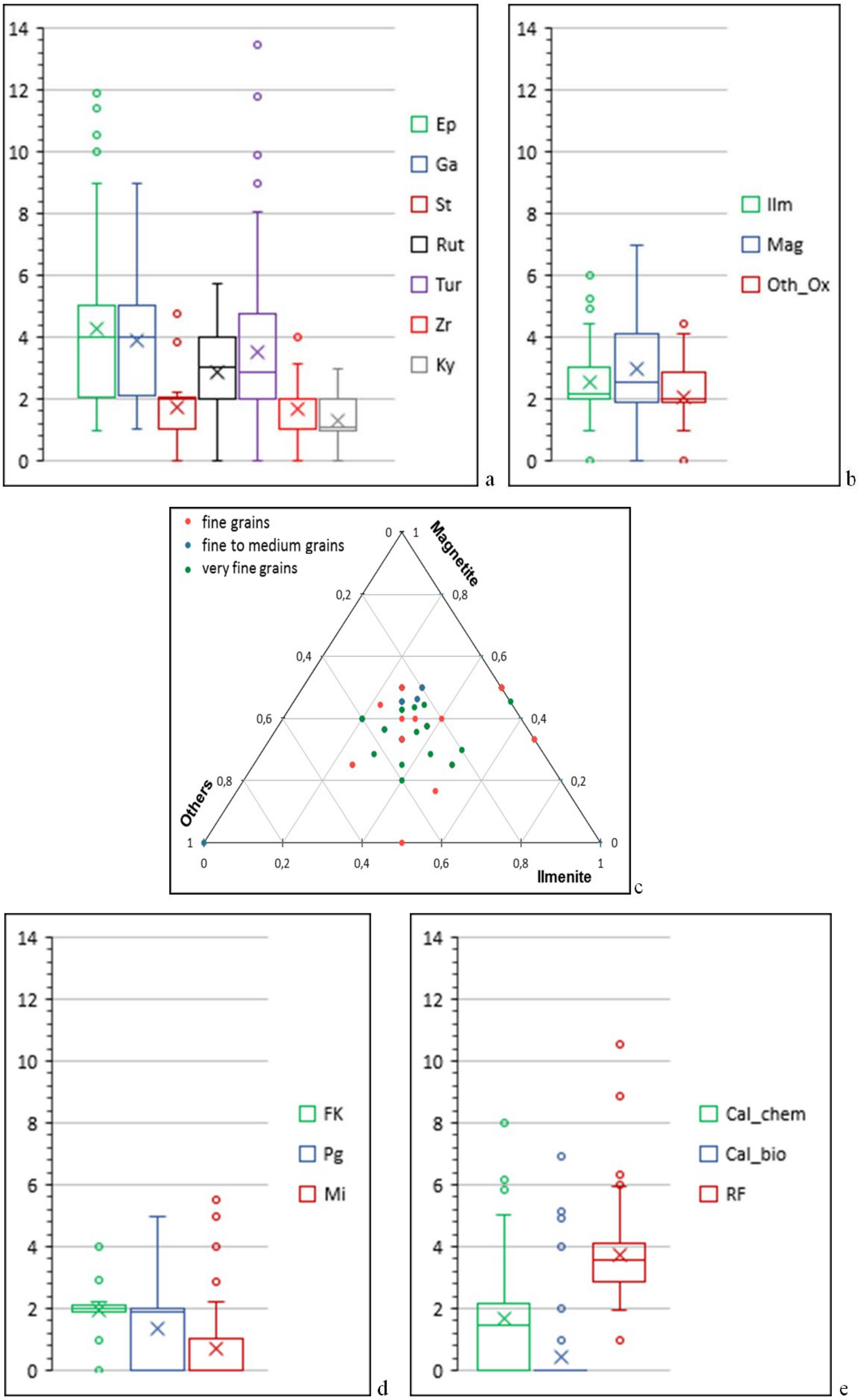


Fig. 12. Proportions of different minerals within the sandy stocks of Merzouga-Tafilelt dunes. (a) Heavy minerals, (b) Oxides, (c) Oxide percentage triangle, (d) Feldspars and micas, (e) Rock fragments and calcite. FK – potassium feldspars, Pg – plagioclase, Mi – micas, Ep – epidote, Ga – garnet, St – staurolite, Ru – rutile, Tu – tourmaline, Zr – zirconium, Ky – kyanite, Ilm – ilmenite, Mag – magnetite, Oth_Ox – other oxides, Cal_chem – chemical calcite, Cal_Bio – biodetritic calcite, RF – rock fragments

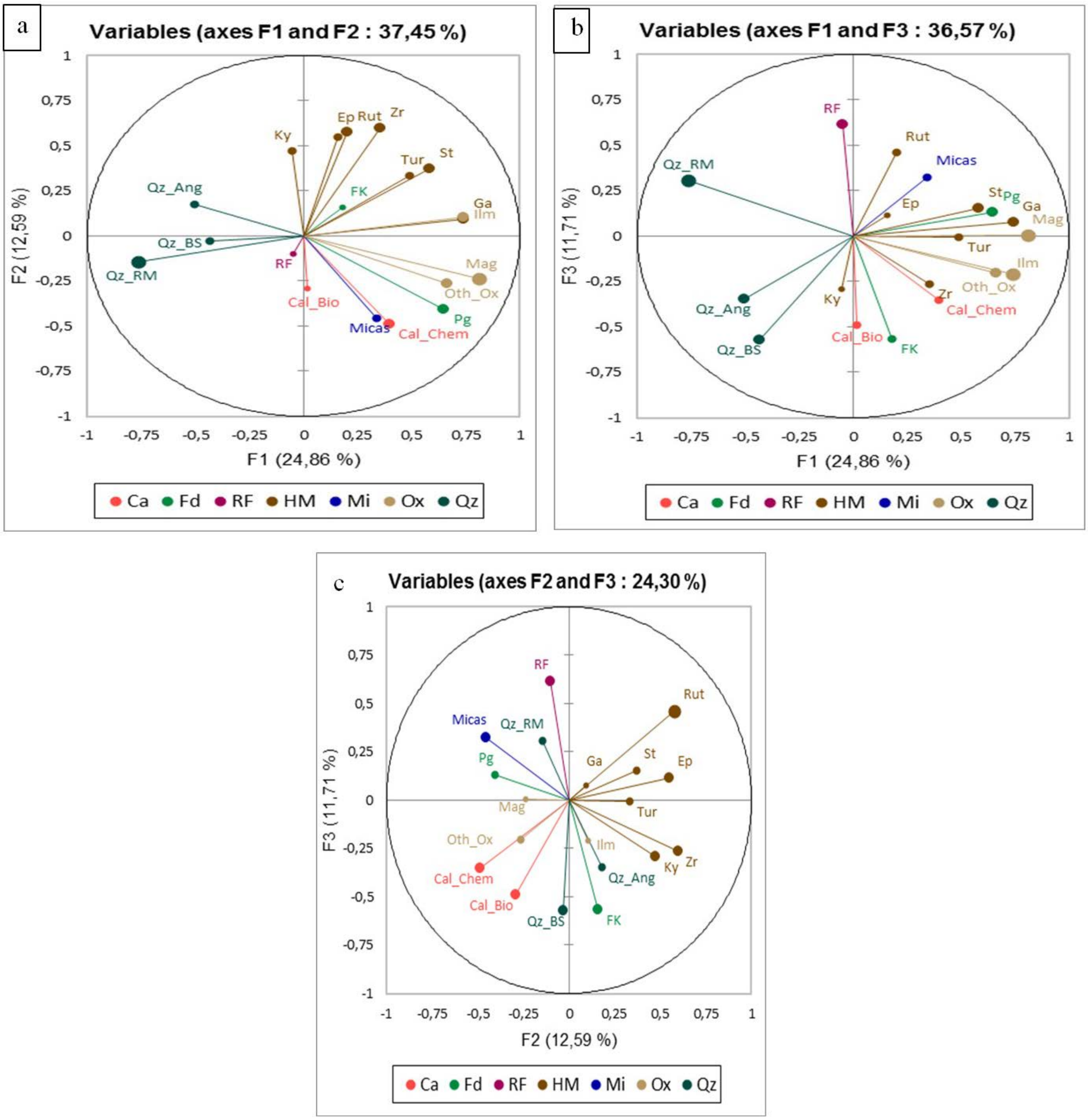


Fig. 13. PCA variable graphs for Merzouga-Tafilelt dune sand: (a) F1F2, (b) F1F3, (c) F2F3, Qz_Ang – angular quartz grains, Qz_RM – round mat quartz grains, Qz_BS – blunt shiny quartz grains, FK – potassium feldspars, Pg – plagioclase, Mi – micas, Ep – epidote, Ga – garnet, St – staurolite, Ru – rutile, Tu – tourmaline, Zr – zirconium, Ky – kyanite, Ilm – ilmenite, Mag – magnetite, Oth_Ox – other oxides, Cal_chem – chemical calcite, Cal_Bio – biodetritic calcite, RF – rock fragments; Colored groups: Qz – quartz, Fd – feldspars, HM – heavy minerals, Ox – oxides, Ca – calcite.

opposed to mat round quartz and rock fragments. Rutile is opposed to calcite.

Heavy minerals show a strong negative correlation with quartz, particularly with mat round grains, but weak with shiny blunt and angular grains. They are very weakly intercorrelated and can be grouped as follows: 1 – garnet, 2 – staurolite, tourmaline, epidote and rutile, 3 – zircon and kyanite.

Oxides show a strong negative correlation with quartz. Their intercorrelation is positive and strong between magnetite and ilmenite, moderate between magnetite and other oxides, and weak between ilmenite and other oxides. The negative correlation of oxides with total quartz is essentially explained by that of round mat quartz against each of the oxides. Garnet is also positively correlated with oxides, particularly with ilmenite.

Plagioclases and potassium feldspars coexist but are not intercorrelated. Plagioclases show a weak negative correlation with quartz. Potassium feldspars show a weak negative correlation only with mat round quartz. Micas are very

Table 1. (a) Contributions of variables to the principal components (%) and (b) Squared cosines of variables.

a

Mineral	F1	F2	F3
Qz_Ang	5.391	1.322	5.424
Qz_BS	3.981	0.036	14.740
Qz_RM	12.425	0.875	4.179
FK	0.684	1.062	14.361
Pg	8.885	6.947	0.792
Mi	2.454	8.647	4.776
Ilm	11.553	0.432	1.982
Mag	13.861	2.316	0.000
Oth_Oxy	9.293	2.936	1.861
Cal_Pail	3.325	10.027	5.630
Cal_Coq	0.006	3.512	10.796
Ep	0.538	12.645	0.599
Ga	11.662	0.380	0.279
St	7.217	5.806	1.082
Ru	0.859	13.783	9.510
Tu	5.107	4.624	0.001
Zr	2.655	14.861	3.138
Ky	0.056	9.366	3.816
RF	0.047	0.424	17.035

b

Mineral	F1	F2	F3
Qz_Ang	0.255	0.032	0.121
Qz_BS	0.188	0.001	0.328
Qz_RM	0.587	0.021	0.093
FK	0.032	0.025	0.320
Pg	0.420	0.166	0.018
Mi	0.116	0.207	0.106
Ilm	0.546	0.010	0.044
Mag	0.655	0.055	0.000
Oth_Oxy	0.439	0.070	0.041
Cal_Pail	0.157	0.240	0.125
Cal_Coq	0.000	0.084	0.240
Ep	0.025	0.302	0.013
Ga	0.551	0.009	0.006
St	0.341	0.139	0.024
Ru	0.041	0.330	0.212
Tu	0.241	0.111	0.000
Zr	0.125	0.355	0.070
Ky	0.003	0.224	0.085
RF	0.002	0.010	0.379

weakly negatively correlated with quartz, not correlated with potassium feldspars, and have a weak positive correlation with plagioclases.

Rock fragments show few correlations. They are negatively and weakly correlated with shiny blunt and angular quartz, as well as with potassium feldspars.

Chemical calcite shows weak correlations with feldspars, oxides, and garnet, and against mat round and angular quartz. Biodetritic calcite, on the other hand, present in very few samples, did not show any trends.

INTERPRETATION AND DISCUSSION

Aeolian Evolution

The segmented granulometric fractions of the studied area consist of well-sorted sand, transported and deposited by wind with little fluctuating dynamics. The very fine grain fraction was mobilized by wind of extremely low energy, while the fine grain fraction was influenced by low-energy wind. The fine-to-medium fraction was transported by slightly stronger, yet still low-energy, wind.

The average grain sizes of the sand of Merzouga-Tafilelt are similar to those observed in many places in the Moroccan desert, particularly in the Mezouga and Erfoud regions, as reported in the works of (Benalla *et al.*, 2003; Kabiri *et al.*, 2003; Boudad, 2004). Consistent with Friedman's research (1961), continental dunes generally have a sorting index (standard deviation) below 0.5 kabi, indicating that they are well-sorted.

Aeolian sand is characterized and classified by (Besler, 2008) based on the position of their mode and the shape of their distribution. These types of aeolian sand have been associated with different stages of aeolian evolution, also known as aeolian ages, which originate from alluvial sources such as essentially endorheic rivers, or other sources such as sand resulting from the weathering of pre-existing rocks like granitic arenas or sandstone or coastal sand. Since our study area is distant from coastal areas, the latter source is excluded.

The homogeneous sand and the fractions resulting from the segmentation of heterogeneous samples of Merzouga-Tafilelt seem to correlate well with the types defined by Besler (2008) for aeolian mobility. Indeed, the fraction of very fine grains in the studied area would correspond to the young dune sand which represents the first stage of the evolution of the aeolian terrace sand. The terrace sand is the alluvial sand stock source mainly composed of very fine grains associated with minor fine and medium grains, which are deposited on the banks of rivers and cleared by deflation of silts and clay. The young dune sand is made up of the 63–125 μm fraction mobilized by the wind towards the interior of the land to form small longitudinal dunes and young barchans abandoning the coarser grains on the alluvial terrace. The second stage of evolution, defined by Besler (2008), will constitute the active crests of the dunes formed after deflation of the very fine fraction 63–125 μm and concentration of the fine fraction 125–250 μm of the active crest sand. Its equivalent in the studied area could correspond to the fine fraction 100–220 μm. The active crests are found on the primary longitudinal and transverse dunes, on the barchans, as well as on the secondary dunes of the draa after their reactivation. The mixture of the two previous fractions can constitute the dome sand, in the dome-type dunes, by repeated supply of very fine grains, at the same time as the deposition of the coarser fractions. The third stage of evolution, defined by Besler (2008), is that which corresponds to the inactivation of dune sand by progressive loss of the 125–250 μm fraction in favor of the 250–500 μm fraction of the inactive crest sand. It is mainly found in the lower parts of the longitudinal and transverse dunes, as well as at the edge of the barchan-type dunes. The equivalent of this theoretical fraction in the study area would correspond to the 180–315 µm fraction. The simple stages which preceded characterize the quasi-stationary dunes where only the crest is in permanent movement. The fourth aeolian age is that of the old barchan sand, where the 250–500 µm fraction takes advantage over the fine fractions of the inactive crest sand. This fraction is absent in our study area. This aeolian evolution characterizes the Barchan type dunes still in migration. The ultimate stage of this wind evolution, according to Besler (2008), would correspond to a single-mode sand between 250 and 500 µm, thus representing the last stage of the granulometric evolution of dunes in modern aeolian systems.

These three fractions, each alone, do not always form the sand of the studied area. As already seen, they form a heterogeneous mixture with varying proportions. Each of them is representative of a kinetic energy of the mobilizing wind. The lowest energy being responsible for the formation of young dune sand, the average energy forms the sand of active ridges and the highest energy, in the studied sector, forms the sand of inactive ridges. These mixtures could be explained according to Besler (2008) by complex processes including degeneration in wind dynamics. The author highlighted a certain number of degenerative sand stocks that take place when a certain wind stability takes over from mobility. The sand-sheet is characterized by a long tail with a reduced mode of residual coarse grains, which can exceed 1000 µm, associated with a modal fraction of 63–125 µm, and protecting it from any deflation. Deflated sand is bimodal mixtures of a fine fraction, trapped because the sand stock is no longer mobilized, and another medium one. Plinth sand is characterized by a plateau spread out from 63 to 500 µm, sometimes with a slight peak in the fines. They characterize a stage of maximum stability where all deflation is absent and the accumulation of all imported fractions.

The constituent fractions of the three main configurations of dune sand stocks in Merzouga-Tafilelt—unimodal, bimodal, or trimodal—are well sorted and composed of sand that has undergone efficient sorting during their transport by the wind that carried them.

1. Unimodal homogeneous sand, with a broader distribution compared to the segmented fractions, indicate a relatively good overall dynamic sorting. They may correspond to mixtures of non-individualized fractions:

- Sample 386 could correspond to dome sand, a balanced mixture of young dune sand and active crest sand.
- Sample 431 appears to be a mix primarily of active crest sand with a minor contribution from inactive crest sand.
- Sample 378 likely represents a composition where inactive crest sand is dominant, active crest sand is minor, and young dune sand is present in very small proportions.

The correlation of these three distributions with the sand types defined by Besler (2008) suggests that they result from a continuous and ongoing aeolian evolution. This progression occurs from young dune sand to inactive crest sand, passing through the intermediate stage of active crest sand. Each of these sand deposits represents an incomplete transitional stage within this evolutionary process. This transformation is likely driven by a gradual increase in wind strength, leading to an incomplete deflation of finer fractions while coarser fractions continue to be deposited. Sample 435, on the other hand, could correspond to an aeolian degeneration process tending toward a dominant stock of young dune sand, accompanied by coarse residual deposits forming a more or less developed tail, characteristic of sheet sand.

2. Bimodal Sand Stocks likely correspond to mixtures of active crest sand and young dune sand, with varying proportions, though they are most often dominated by active crest sand. This mixture could be explained by the simultaneous deposition of both fractions due to alternating wind dynamics over short time spans. The presence of a reduced tail of medium grains, extending up to 500 µm, suggests the occasional influence of stronger, yet exceptional, wind events. The aeolian degradation process proposed by Besler (2008) would not account for this configuration, as coarse fractions are nearly absent.

3. Three-Mode Distribution likely represents a three-component mixture dominated by active crest sand with minor contributions from young dune sand and inactive crest sand. This configuration probably results from the evolution of the bimodal distribution, incorporating inactive crest sand into the mix. The simultaneous deposition of these three fractions is likely due to alternating wind dynamics over short durations. The variant of this distribution may be attributed to the coexistence of two wind dynamics, leading to a dominance of inactive crest sand with a secondary presence of active crest sand. The presence of a reduced tail of medium grains, extending up to 500 µm, suggests the occasional influence of stronger, yet exceptional, wind events. This configuration indicates the early stages of aeolian degeneration, marking a transition toward the more stable aeolian phases, where finer particles are no longer removed while stronger wind continue to deposit coarser grains and readjust distributions. These sand stocks likely correspond to deflated sand.

Wind mobility is a factor responsible for the proper sorting of transported and deposited sand, and it is particularly effective when it acts on fine grains (Besler, 1983). The granulometric evolution interpreted from our analysis has then supported the mobility of the sand studied. Moreover, the analysis of the frequencies of the homogeneous sand fractions obtained from segmentation and the response diagram has confirmed, due to the small grain size and their high degree of sorting, that this sand is indeed aeolian sediments currently undergoing mobilization.

Transport modes and Mineral Composition

The factorial analysis of the various components of dune sand grains from Merzouga-Tafilelt revealed that all accessory minerals are antagonistic to quartz grains, regardless of their shape. Dune sand from Merzouga-Tafilelt formed dunes of aeolian origin. However, the heterogeneity of quartz shape and appearance indicates diverse genetic modalities. Angular quartz grains, which are a minor component of quartz grains, may have been mobilized and deposited by wind either directly onto their source substrate or near it. Grains that have undergone substantial transport, mat round and shiny blunt, are thus in the majority compared to angular ones. The presence of shiny blunt quartz in small proportions suggests that at least part of the sandy stock in the study area underwent fluvial transport before being mobilized by wind action over short distances. Mat round quartz grains, dominant, could correspond either to grains of pure aeolian origin or to alluvial sand that was transported by wind over long distances or repeatedly reworked over long periods, thus masking their alluvial origin. Mixed origin was proposed by Hrou (1991), who indicated that the sandy masses responsible for the sanding of the Jorf and Hannabou regions were mobilized by the rivers of Rhéris, Ziz, and Guir before being deposited downstream of the basin of these rivers in the form of sand beds.

The lack of correlation between the quartz forms and grain size disproves any potential relationship between granulometric evolution and transport mode. Indeed, regardless of the size of the fraction concerned, i.e., regardless of the aeolian evolution it underwent, it would be composed of grains deposited either without transport, very close to their sources, or mobilized more or less far from the source by wind alone or by wind combined with fluvial transport. Correlatively, regardless of the transport modes of the origin of the grains, they would differentiate according to the aeolian dynamics to constitute the different grain size fractions of the sandy stocks.

The positive correlation between oxides and garnet suggests a likely common origin, potentially igneous, basic magmatic, or high-pressure metamorphic. However, the possibility of an association between two different source facies—acidic and basic, for example—though geographically close, cannot be excluded. The positive correlation between kyanite and zircon suggests that their source may correspond to high-pressure metamorphic rocks. As for the positive correlation between staurolite, tourmaline, epidote, and rutile, it indicates a source composed of facies from regional metamorphism at sufficiently high pressure and temperature. This assemblage of resistant minerals, including oxides and heavy minerals, likely originates from the igneous formations of the High Atlas and the Anti-Atlas (Parfenoff *et al.*, 1970).

The ability of plagioclase and potassic feldspars, as well as micas, to weather explains their very small proportions, making it difficult to distinguish possible correlations, and subsequently potential origins. However, they are known to be predominant in acidic magmatic rocks, common in mafic rocks, and exist, as well, in some metamorphic and sedimentary rocks. Such rocks are indeed found nearby in the Atlas Mountains.

The rock fragments indicate a sedimentary origin, specifically sandstone. The two petrographically identified origins of the calcite in the dune sand of Merzouga-Tafilelt — biogenic and chemical — have already been discussed by Boudad (2004), who formulated three hypotheses to explain the origin of carbonates: (1) dissolution of limestone formations from the High Atlas and the Hamada of Meski, (2) biogenic origin within soil, and (3) aeolian dust from the nearby large Hamadas of southeastern Morocco, mobilized by dust wind accompanying the Chergui (eastern wind).

CONCLUSIONS

The dune sand of Merzouga-Tafilelt are composed, on average, of two-thirds quartz grains. The remaining third consists of grains of various compositions and proportions, primarily oxides and heavy minerals, along with minor amounts of feldspars, micas, sandstone rock fragments and calcite. Clay components are rare or absent due to wind deflation.

Magmatic and metamorphic formations constitute the primary source of the studied sand deposits, with a secondary contribution from sedimentary sandstone and limestone rocks. The Anti-Atlas formations, predominantly, along with those of the High Atlas, supply the Merzouga-Tafilelt basin through both aeolian and hydrological transport processes.

The quartz grains of dune sand, obviously aeolian, are mainly mat round, with a minority of shiny blunt and angular grains. Genetically, angular quartz grains would have been deposited after mobilization by wind, without significant transport, from their source substrate. Shiny blunt grains likely result from the mobilization of alluvial sand without substantial aeolian transport. As for mat round quartz, they would indicate exclusive or at least predominant aeolian transport, which would have erased any prior fluvial history.

Regardless of the transport mechanism involved, aeolian dynamics have led to the differentiation of three essential, well-sorted fine-grained fractions, characterized by sharp, often well-defined modes with relatively stable positions. These fractions correspond to highly sorted sand: very fine (63–125 μm), fine (100–220 μm), and fine to medium (180–315 μm), which are indicative of dune crest mobility. These fractions likely combined in varying proportions to form the unimodal, bimodal, or trimodal sand deposits observed in the study area.

By correlation with the genetic framework proposed by Besler (2008), the homogeneous fractions of the polymodal sand in the Merzouga-Tafilelt dunes appear to reflect successive stages of gradual aeolian mobility, driven by an evolving wind regime of increasing intensity. This process involves the progressive deflation of the finest fraction while coarser fractions are progressively deposited. The genesis of this sequence would begin under a low-energy regime, with the aeolian mobilization of very fine sand, toward the inland areas, which form young dunes. As wind energy increases, these very fine sand undergo deflation and are replaced by fine sand which then constitutes the active dune crests. Under even stronger wind, fine to medium sand replaces the deflating fine sand to form inactive crests. A reversal of this evolutionary trend could result in the formation of dome sand through replenishment with finer fractions.

The characteristic sand mixtures of the dunes in the studied area seem to represent intermediate stages of aeolian evolution between the stages defined for homogeneous sand by Besler (2008). These mixtures likely consist of multiple well-sorted pure fractions, each deposited under specific wind regimes. When wind energy decreases, the finest grains are transported and deposited. Conversely, when energy increases, the finer fractions are deflated, while coarser grains are deposited. This evolutionary pattern aligns with the hypothesis of aeolian mobility. Various types of sand mixtures have been observed in the dune sand of the study area, with active crest sand most frequently dominating over young dune sand and/or inactive crest sand.

The following mechanisms may have acted, either jointly or differentially, to generate the characteristic sand mixtures observed in the dunes of the study area: simultaneous deposition of various modal fractions due to wind with multiple dynamics alternating over short durations and/or degeneration of the aeolian evolution towards aeolian ages characteristic of wind stability, where the finer fractions are no longer swept away, while stronger wind continue to transport coarser grains, thereby readjusting the distributions to the deflated sand or sheet sand.

The results obtained in this study highlight the predominant role of aeolian dynamics in the formation of dunes within the Merzouga-Tafilalet region, revealing significant granulometric variations. The analysis also enabled a precise identification of the mineralogical constituents of the sand deposits. These observations provide new insights into sand transport mechanisms and their temporal evolution. However, this preliminary study warrants further investigation through systematic sampling and detailed field observations to explore potential correlations between mineralogical composition, granulometric characteristics, and the morphology and structure of the dune formations in the studied region.

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Conflicts of interest

The authors declare no conflicts of interest.

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