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ARTICLE

Mineralogical Characterization of Dune Sands in Eastern Morocco (Figuig-Tendrara Region): Mineralogical Composition and Source of Sand Stocks

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ABSTRACT

The aim of this article is to study and reveal the mineralogical composition of dune sands from the Bouarfa Figuiget region (eastern Morocco) and to find the potential source of these dune sands. The mineralogical study was made by combining field studies to collect samples and determine the facies of the surrounding area with labortory studies, including geochemical analysis (DRX analysis), morphoscopic study of the sands under a binocular magnifying glass according to the fractions making up these sands, heavy mineral extraction and analysis under a microscope, and calcimetric analysis. The results revealed two main categories of minerals in sandy deposits: light and heavy minerals. These include quartz, plagioclase feldspar, calcite platelets, and fragments of greyish, greenish, and whitish rock. Quartz was the dominant mineral. Heavy minerals include dark (opaque) minerals such as garnet, tourmaline, epidote, zircon, rutile, and rock fragments. This composition is the result of erosion, transport, and deposition processes in the crystalline sandstone and sedimentary formations of the eastern High Atlas, which feed the study area via aeolian pathways, including winds from ERG CHBI. The quartz grains in the dune sands of the eastern region, accumulated by wind action, are mainly round, matte grains of aeolian origin. The mineral associations observed show the presence of two types of sandy deposits: (1) Sand dominated by matte, round quartz grains (fraction 225 µm), associated with accessory minerals (garnet, tourmaline, zircon, rutile, kyanite, and epidote), oxides (magnetite and ilmenite), and rock fragments of mixed mineral, crystalline, and

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sedimentary origin. (2) Totally dominant matte round quartz sand associated with iron oxides and a few rock fragments (fractions 142 µm, 180 µm and 357 µm). Sand with fraction 225 µm consists almost entirely of quartz (8%) with garnets and a few rock fragments. These results suggest that the variation in the composition of the dune sands in the study area depends on the nature of the granulometric fraction studied, and therefore on the variety of sources feeding the sands studied (Chott Tigri, crystalline and sedimentary formations of the Eastern High Atlas).

Keywords: High Eastern Atlas; Sand Deposits; Calcimetric Analysis; Heavy Minerals; Crystalline Sources

1. Introduction

Sand is a natural material composed of grains with diameters typically ranging from 2 mm to 0.063 mm. It forms through the erosion of rocks by agents such as water, temperature, and wind. The fracture and chemical decomposition of larger grains contribute to the formation of sand grains, and due to the varying sizes of these grains, differences in their mineralogical and chemical compositions are observed. These differences reflect the chemical and physical properties of the parent material [1].

Mineralogically speaking, sand contains primary minerals such as silica, potassium feldspar and mica, as well as secondary compounds and minerals resulting from chemical weathering processes, such as free oxides, notably iron and aluminum oxides.

Sand grains correspond to small pieces of rock or minerals (rock fragments) or minerals, reflecting the origin of the parent rock from which these minerals were formed. They are found in different parts of the earth's crust [2].

A preliminary study of the Oued Rheris deposits [3–8] indicates that volcanic and metamorphic minerals can only be derived from distal fluvial inputs associated with the Atlas structural domain. However, it cannot be ruled out that fine eolian sands may have originated in the Anti-Atlas region.

Sands can be categorized into two main types: light sands, which are the most abundant, and dark sands. Light sands primarily consist of light-colored minerals such as quartz, calcite, mica, and potassic feldspar [9]. These sands are commonly used in construction, glass manufacturing, ceramics, and other industries. On the other hand, dark sands are composed mainly of heavy minerals with a density greater than 2.87. They originate from the erosion of rocks rich in minerals like ilmenite, rutile, garnet, tourmaline, and zircon. Some of these heavy minerals, such as tourmaline, certain varieties of garnet, and zircon, are valued in jewelry. Others, including monazite, specific types of garnet, and ilmenite, serve as sources of trace elements and rare earth materials essential for high-tech applications, making them highly sought after.

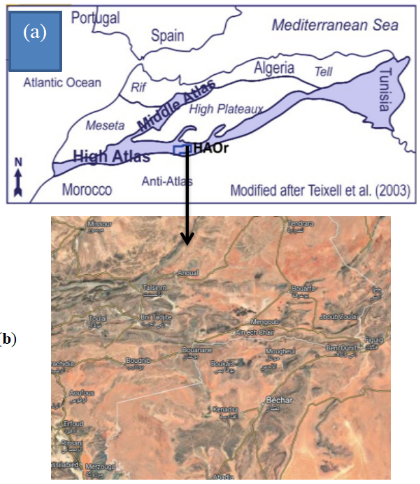
Our study aims to understand the processes of silting, which have led to desertification, salinity, soil erosion and the encroachment of sand on cultivated land, by analyzing the granulometry [10], the mineralogical composition of sand via morphoscopic study, X-rays, calcimetry and the study of heavy minerals, in order to determine the potential sources of these sands and thus mitigate the desertification process.

2. Geographical and Climatic Context

The study area is located in the Eastern High Atlas of Morocco (**Figure 1**), bordered to the north by the High Plateaus and to the south by the pre-Saharan zones of the Colomb-Béchar basin. It forms an extension of the limestone High Atlas, encompassing the massifs of Midelt, Rich, and Anoual to the west, and extends eastward in a NE-SW direction to connect with the Algerian Saharan Atlas. This region is characterized by a succession of anticlines and tabular massifs, separated by closed plains filled with Quaternary alluvial deposits.

Wind roses are more star-shaped, indicating a predominance of winds from collateral points: SW, NW, and NE [12]. In summer, easterly winds dominate. The Chergui, an east to southeast wind, is accompanied by very high temperatures, causing a drop in temperature, most often in summer, 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.



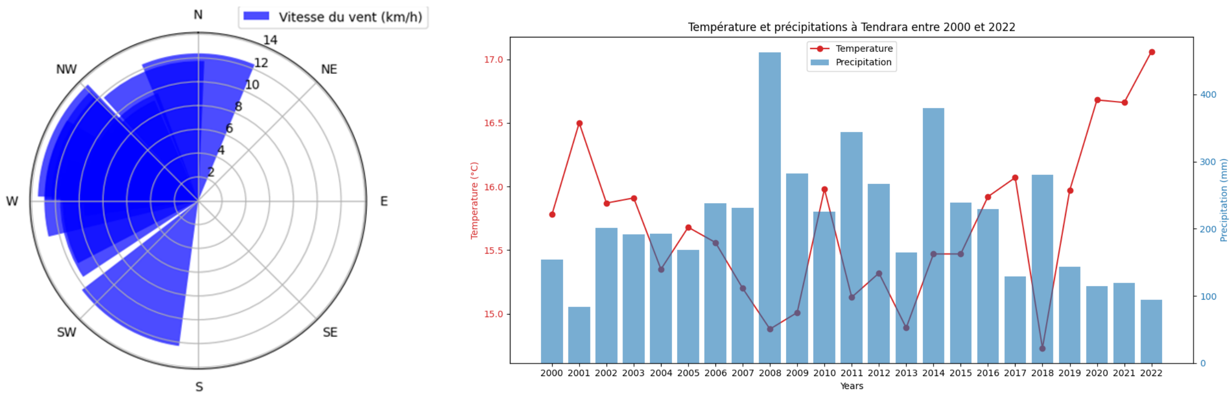
(b)

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 region is dominated by an arid climate, characterized by cold winters and hot summers. Precipitation is low, averaging 120 mm over a 22-year period (2000–2022). Annual precipitation is highly variable from one year to the next, with temperatures ranging from 38 °C to 45 °C, and even up to 48 °C. The amount of precipitation varies greatly from month to month (**Figure 2b**).

From a hydrogeological perspective, 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 Lias limestones;
- The potential aquifer of the Dogger.



(**a**) (**b**)

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

3. Geological Setting

Geologically, according to Michard[13], the Eastern High Atlas forms a depression corresponding to the Tamlelt buttonhole, 120 km long and 50 km wide. In this region, Precambrian and Paleozoic terranes outcrop in the form of buttonholes. This depression is bounded by Meso-Cenozoic formations, which are also found in the center of the buttonhole in the form of control lenses. The Meso-Cenozoic atlasic cover outcrops on a basement mainly made up of Cambrian, Ordovician and Silurian fossiliferous terrains, as well as extensive lenses of Precambrian basement (**Figure 3**).

Structurally, the Eastern High Atlas is marked by polyphase faulting[14–16]. Since the Jurassic period, the region has undergone extensional phases with stretching directions of NNE-SSW and NE-SW, resulting in significant dislocation of Jurassic dolomites and limestones. The Tertiary compressive phase, responsible for the uplift of the entire High Atlas chain, reactivated the main faults, transforming them into reverse faults and, locally, into strike-slip faults, such as those affecting the Tamlelt plain.

According to Milhi et al.[17], several Hercynian and Triassic veins and dykes (microgranites, microgabbros, diabases) intrude the series. The microgranites are poorly altered and composed of quartz, potassium feldspar (orthoclase) and microcline. The green rocks, which are fairly weathered, are composed of microgabbros and diabases. They have a microlithic background crystallized with minerals of epidote, plagioclase, pyroxene (augite) and pyrite. Amphibolite dykes are scarce.

From a metallogenic standpoint, mining studies have focused primarily on the main mines, namely manganese at

Bouarfa, barite at Zelmou and gold-bearing copper at Menhouhou. Other showings and occurrences have only been briefly studied as part of regional surveys.

To the best of our knowledge, the main "academic" works carried out in the area are those by Sharp et al.[18–24].

With regard to geological mapping, and in addition to the small scales of 1/1,000,000 (which covers the entire 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[25] and at 1/50,000 by Milhi et al.[26].

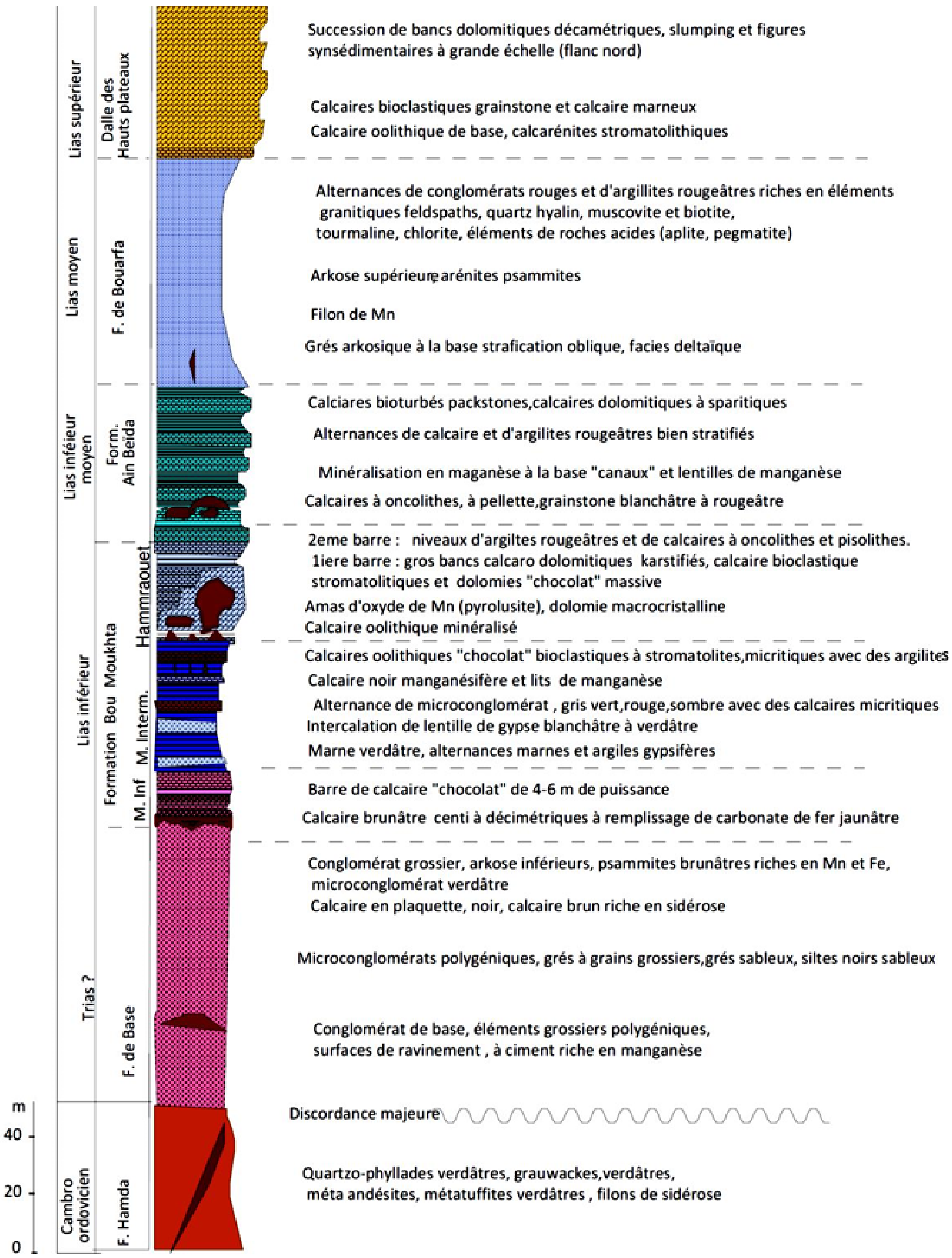


Figure 3. Stratigraphic column of the Bouarfa sector by Bahi et al.[27].

4. Materials and Methods

Two approaches were used to study and characterize the mineralogy of sandy accumulations in the eastern regions (**Figure 4**). The first approach consisted of sampling and observing facies: samples were taken in the field, on the surface, from the various sandy accumulations (barkhane, nebkhane, etc.). The second approach was to determine the facies encountered in the study area. In general, these field missions involved geological prospecting, facies recognition and the collection of samples for laboratory analysis. Samples were placed in labelled plastic bags and separated accordingly. 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**).

The aim of this study is the mineralogical analysis of sandy accumulations in the eastern region. A study of wind dynamics in the field and sedimentology in the laboratory has been undertaken[10].

(**a**) (**b**)

Figure 4. Sampling of sands moving in the direction of wind currents in the region: (**a**) of Ain Chouater (Bouanane region, April 2019) and (**b**) east of Merzouga (November 2019).

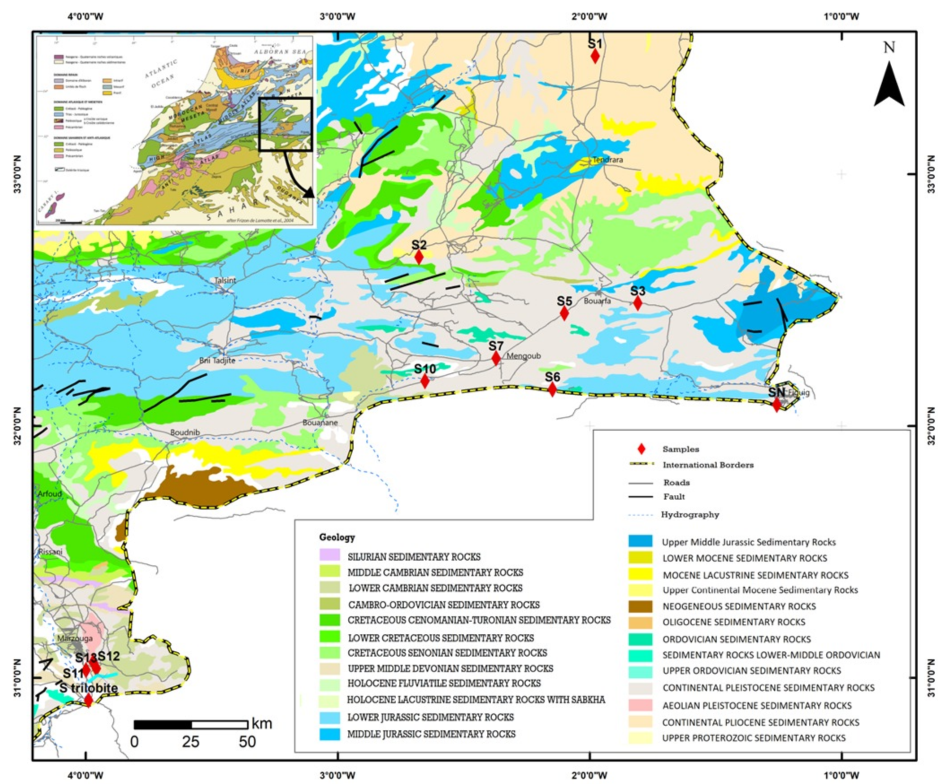


Figure 5. Sampling sites for mineralogical analysis of eastern Morocco.

4.1. Morphoscopic Analysis

Morphoscopic petrographic analysis was carried out using a binocular magnifying glass. The criteria observed were color, shape and luster [28]. A hundred grains were counted. Observation was carried out on each of the representative modes in each sample. Heavy minerals were separated with bromoform before observation, to facilitate mineralogical determination.

Grain morphoscopy enables us to statistically determine the composition and petrographic and mineralogical proportions of the grains making up sandy deposits [29]. Analysis of the shape and appearance of detrital quartz grains has provided clues as to their modes of transport. In addition, the petrographic description of non-quartz grains enabled us to identify their mineralogy and deduce their origin.

4.2. Mineralogical Analysis

In addition to petrographic observation, X-ray diffraction was used to qualitatively identify the mineralogical composition and crystalline structure of the grains present in the sands studied. A portion of dried raw sand was crushed, then analyzed using an X-ray diffractometer (XRD). The various chemical constituents were identified by analyzing the peaks corresponding to their specific 2θ values.

4.3. Calcimetry

is used to quantify the carbonate content of sediments. This method is based on measuring the volume of carbon dioxide released when a known quantity of sediment is reacted with hydrochloric acid. The volume of CO_2 is measured in a manometer tube after the sample has reacted with hydrochloric acid, according to the following reaction:

$$CaCO_3 + 2HCl \rightarrow CaCl_2 + H_2O + CO_2.$$

4.4. Heavy Minerals Analysis

Every rock contains accessory materials, some of which are distinguished by their chemical stability and high density. When this density exceeds 2.89, we speak of "heavy minerals". These heavy minerals, present in very small proportions, accompany the rock throughout its erosion and various sedimentary processes. They act as markers, providing information on rock origin and sediment transport conditions [30].

Mineral separation, according to Parfenoff, Pomerol and Tourenq [28], can be achieved by various methods, such as:

- Density separation using a dense liquid,
- Magnetic separation,
- Electrostatic separation,
- Dielectric separation,
- Electrochemical separation,
- Shaking table separation,
- Separation by sorting or using a binocular magnifying glass.

In our experiment, we opted for the densimetric separation method. This involves immersing the minerals in a liquid of known density. Minerals with a lower density than that of the liquid float to the surface, while those with a higher density settle to the bottom of the settling funnel. The dense liquid used is bromoform (CHBr3), with a density of 2.89.

4.5. Principal Component Analysis (PCA)

We used Principal Component Analysis (PCA) to analyse the relationships between the various elements. PCA is a multivariate graphical processing method that simultaneously represents variables and observations in a two-dimensional space. The orientation of the axes provides information on the relationships between variables and components. Interpretation of the results is based on the analysis of the position of each component in relation to the circumference, as well as the proximity between components and the angles formed by their respective vectors.

5. Results and Discussion

5.1. Diffraction Analysis: X-rays

Binocular microscopic petrographic analysis of the Oriental dune sands revealed a composition dominated by quartz grains (**Figures 6** and **7**), with a minimum of 52%, a maximum of 90% and an average of over three-quarters. X-ray diffraction also confirmed this composition, with silica peaks predominating. Other components were also detected by X-ray diffraction, such as iron and alumina, which do not exceed

10% for most samples, primarily derived from silicates such as feldspars, micas, and heavy minerals (**Figure 6**).

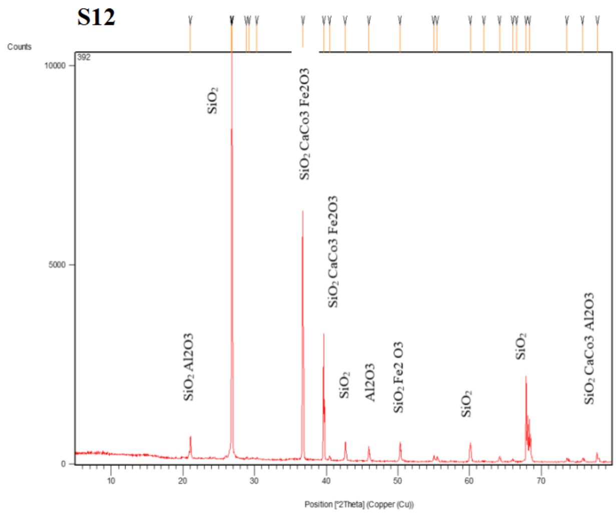


Figure 6. X-ray diffractograms showing the nature of minerals.

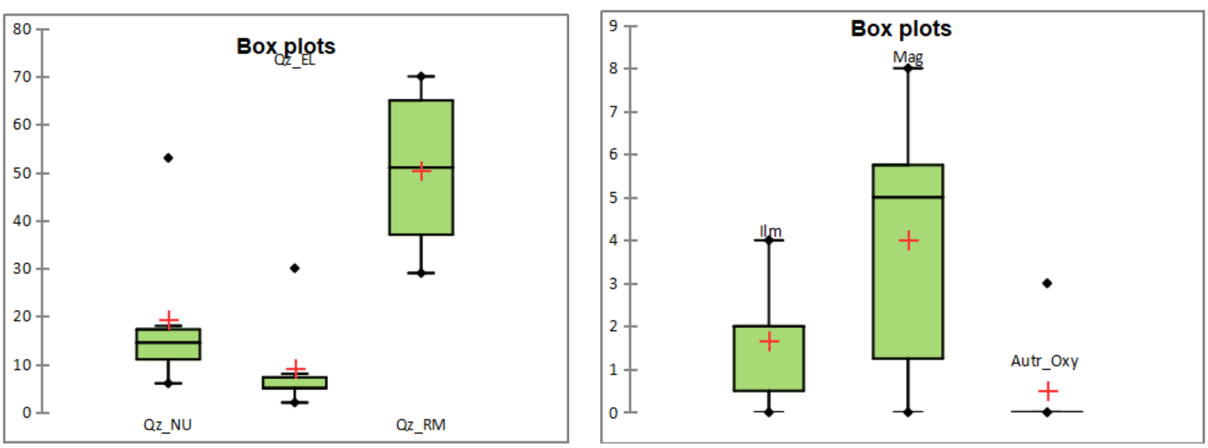
5.2. Morphoscopy and Mineralogical Composition

The morphoscopic analysis of the quartz grains revealed three categories of shape and appearance. Matte rounded quartz grains dominate the quartz stock (**Figure 7a**) and are often the majority (**Figure 7a**), ranging from 29% to 70%, with an average proportion of 50.5%. These are followed by unworn quartz grains, which can sometimes make up the majority of the quartz stock, ranging from 53% to 6%, with an average proportion of 19.33%.

The smooth, dull, shining quartz grains are present in secondary proportions (**Figure 7a**) in the quartz stock and often rank third, with an average of 8%. These grains can be minority components, with a minimum of 2%, but never dominate, never exceeding 33%. Some quartz grains show slight ferruginous coloration.

Since the sands of the Oriental region originate from dunes, their origin is at least partially aeolian. However, the diversity in the shapes and appearances of the quartz grains suggests various genetic processes. The unworn quartz grains, which are in the minority, were likely mobilized and deposited by the winds either directly onto their source substrate or near it.

Given that the sands of the Oriental region come from dunes, their origin is at least partly aeolian. Nevertheless, the diversity in the forms and appearances of quartz grains suggests varied genetic processes. The smooth, dull, shining quartz grains, though minor in number, would have been mobilized and deposited by water transport after being carried by the wind, possibly remobilized over long distances.



(**a**) (**b**)

Figure 7. (**a**) Composition and proportions of quartz types, (**b**) composition and proportion of iron oxides.

Note: Qz_NU: angular quartz grains – Qz_RM: round matte quartz grains – Qz_EL: blunt shiny – Ilm: ilmenite – Mag: magnetite –Autr_Oxy: other oxides.

The dominance of matte rounded quartz grains, either in proportion to other types within the same sample or in the number of samples containing this property, indicates that a significant portion of the sandy stock in the study area corresponds either to grains transported exclusively by the wind or to sands of alluvial origin masked by long-distance or repeated aeolian transport.

Unworn quartz grains, substantial or sometimes dominant components, would have been mobilized and deposited by the wind when its speed weakened, either directly onto their source substrate or near it.

The oxides (**Figure 7b**) are mainly magnetite (4% on average and 8% at maximum), followed by ilmenite (1.7% on average and 4%). The diffraction peaks of the oxides confirmed that their distribution is not balanced between magnetite and ilmenite.

The observation under the binocular microscope showed precisely the noted differences in sand grains' color, morphoscopy, and size.

The extraction of heavy minerals using bromoform, after microscopic observation, revealed the presence of heavy minerals in some samples, while they were absent in others. These included garnet, epidote, zircon, rutile, tourmaline, and disthene (**Figure 8**).

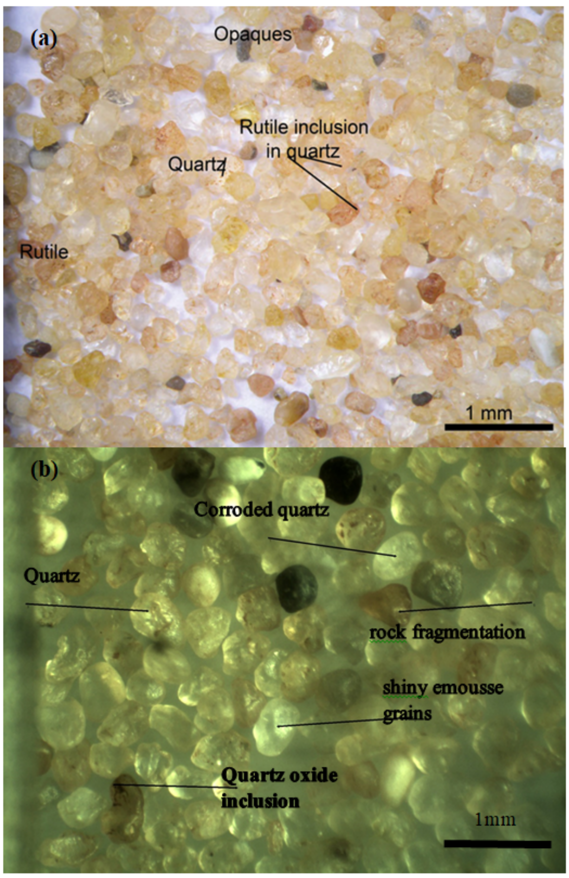


Figure 8. Microphotographs taken with a binocular microscope showing sand grains in sand samples. (**a**) Microphotographs of the fraction 180 µm; (**b**) Microphotographs of the fraction fraction 225 µm.

In addition to the primary mineral component of the sand grains in the Oriental region, which is quartz, other minerals present include feldspars, micas, oxides, heavy minerals, rock fragments, and chemical calcite flakes (**Figure 9**). Feldspars, primarily potassium-rich, account for an average of 2% of the grains, reaching a maximum of 3%. Micas are absent in most samples, appearing in only one sample with a value of 3%.

Heavy minerals and oxides are moderate components in the sands of the studied area (**Figure 9**), representing an average of 5% and 6.5% of the grains, respectively, with maximum values of 13% and 19%. Heavy minerals are virtually absent in the majority of the samples, present only in a minority (samples S1, SN, and S10), in the following order of abundance (**Figure 9**): garnet (0% minimum and 6% maximum), epidote (0% and 4%), rutile (0% and 4% maximum), tourmaline (0% and 5%), zircon (0% and 2%), and disthene (0% and 2%).

Oxides are present in the different sand stocks studied, with varying proportions, sometimes both (ilmenite and magnetite) and sometimes only one of the two, while in one sample (S10), oxides are completely absent.

Rock fragments of various colors—bright green, brown, whitish, yellowish, and grayish, which are difficult to identify—are present in significant proportions, representing an average of 5% of the grains, with a maximum of 6%. These fragments likely correspond to sandstone fragments, indicating a sedimentary origin.

Limestone is represented by a single variety, chemical limestone in flakes, while biological limestone, in shells, is virtually absent (**Figure 9**).

Their percentage relative to the total sample varies from a minimum of 0% to a maximum of 5%.

This mineralogical association is different from that found in the Merzouga-Tafilalet region [10], characterized by silicate minerals whose chemism indicates a calc-alkaline affinity. They are derived from the degradation of metamorphic and magmatic mixtures with a calc-alkaline tendency, where these formations outcrop in the Anti-Atlas range in the Saghro and Ougnat massifs [31].

While the mineralogical composition and morphoscopic analysis of the megabarch sand in Khnifiss National Park, southwest of Morocco, also reflect the richness of K-feldspars, garnets, calcite and dolomite, it indicates a significant contribution from Mesocenozoic formations, consisting of Cretaceous to Pliocene sub-arkosic sandstones and carbonate arenites rich in carbonate arenites [32].

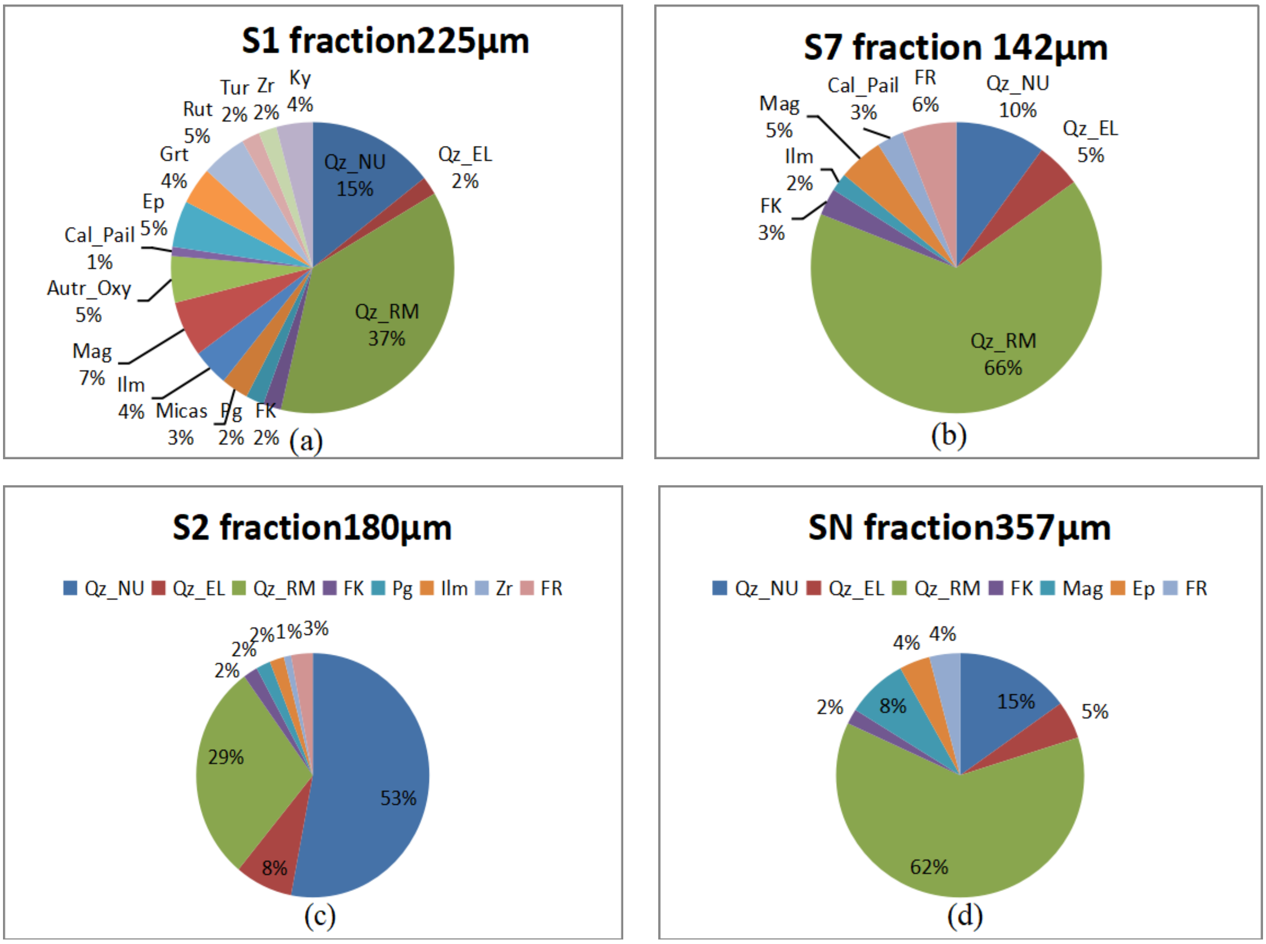


Figure 9. Proportion of minerals in samples by fractions: (**a**) fraction 225 µm, (**b**) fraction 142 µm, (**c**) fraction 225 µm, and (**d**) fraction 357 µm.

Note: Qz_NU: angular quartz grains – Qz_RM: round matte quartz grains – Qz_EL: blunt shiny – FK: potassium feldspars – Pg: plagioclase – Mi: micas – Ep: epidote – Grt: garnet – Ru: rutile – Tur: tourmaline – Zr: zirconium – Ky: kyanite – Ilm: ilmenite – Mag: magnetite – Autr_Oxy: other oxides – Cal: calcite – Cal_Pail: biodetritic calcite – RF: rock fragments.

The segmentation of the sand stocks in the Oriental region is corroborated by a clear and strong negative correlation between the frosted shiny quartz grains and the round matte quartz grains, which is clearly observed on Factor F1 of the PCA diagrams (**Figure 10**). The PCA also shows the absence of correlation between the unweathered quartz grains and the round matte grains, while they exhibit a positive correlation with the frosted shiny quartz grains.

The correlation circle (**Figure 10**) distinguishes three groups:

(1) A first group composed of chemical limestone, ilmenite, tourmaline, micas, disthene, rutile, and zircon.
(2) A second group composed of potassium feldspar, round matte quartz, magnetite, rock fragments, and epidote.
(3) A third group composed of garnet, frosted shiny quartz, and unweathered quartz.

The correlation circle (**Figure 10a**) shows that the association formed by the first group is strongly linked to Factor F1. Factor F1, which explains 43.37% of the total variance, can be interpreted as representing Fe- and Al-rich minerals. Factor 2 explains about 24.55% of the variance and is characterized by the high loading of potassium feldspar, magnetite, and round matte quartz in the positive field, and frosted shiny quartz, unweathered quartz, and garnet in the negative field of the correlation circle.

This arrangement allows us to interpret Factor 2 (F2) as representing the primary minerals (quartz) and garnet. The different types of associations relative to Factors F1 and F2 allow us to positively link the minerals in group (1) and contrast groups (2) and (3).

Factor F3 (**Figure 10b**), which explains 16.47% of the total variance, discriminates between two groups (epidote, magnetite, and rock fraction as a qualitative variable) and another group (rock fragments, particularly frosted shiny quartz). This distribution implies that high levels of epidote are strongly associated with the fractions studied. In contrast, the rock fragments are antagonistic to the grain size fraction and, consequently, to the epidote.

Factor F4 (**Figure 10c**), which represents 15.57% of the total variance, is heavily loaded positively with garnet, weakly with magnetite, rock fraction, and epidote, while it is negatively loaded with potassium feldspar and unweathered quartz. These results suggest that the enrichment in potassium feldspar is due to the presence of unweathered quartz, implying a proximal source of the deposit area.

This set is characterized by the presence of oxides, garnet, and rutile associated with rock fragments of sandstone origin. These source rocks would therefore correspond to the crystalline massifs of the Saharan and Anti-Atlas domains. They would correspond to sediments with a dominant aeolian genetic history that has mobilized, over long distances, alluvial sand grains or grains eroded by the winds.

The frosted shiny quartz grains are accompanied by the lowest rates of accessory minerals. As they become enriched in accessory minerals, they tend to contain epidote and rock fragments.

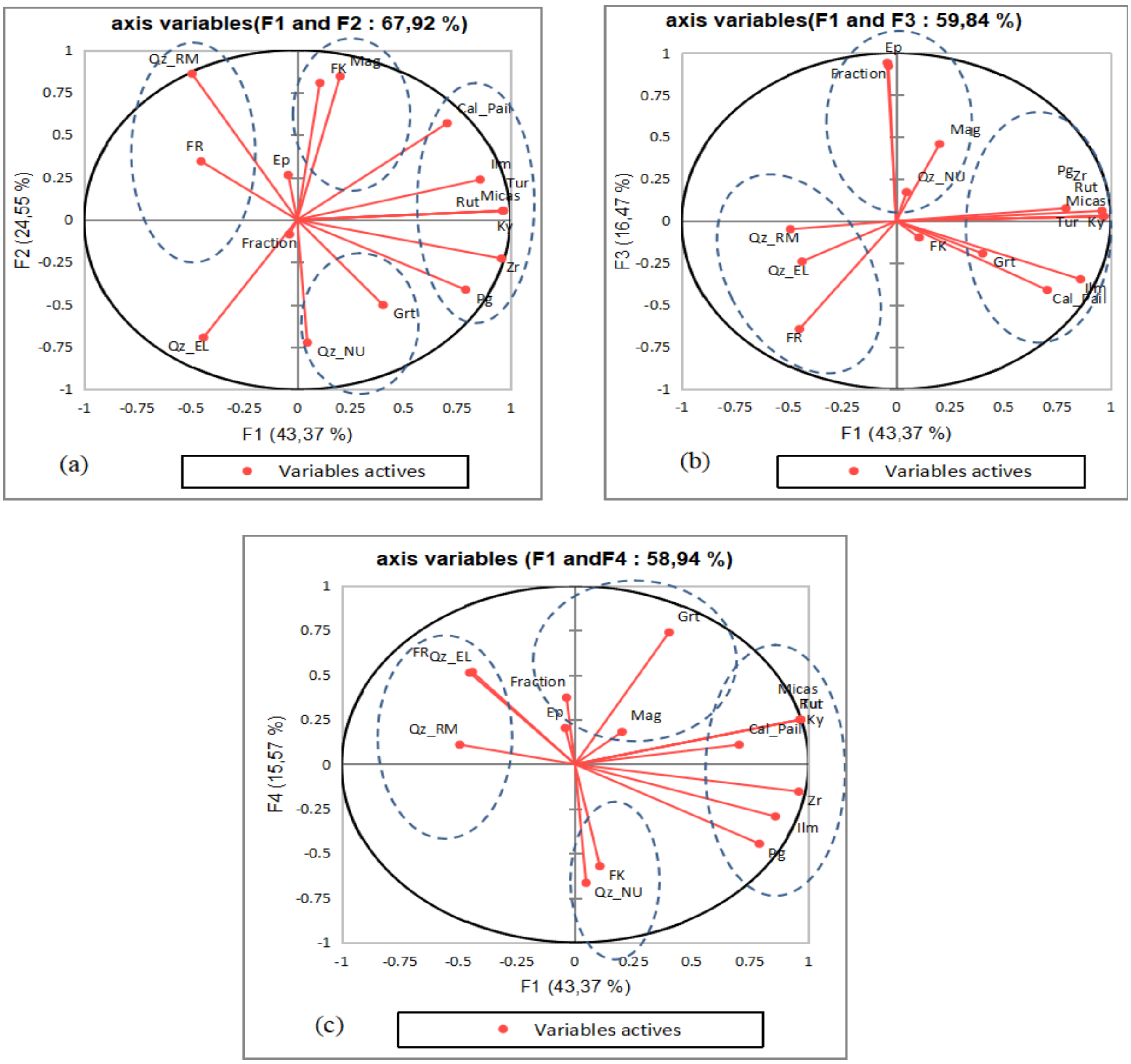


Figure 10. PCA of the mineral constituents of the Dakhla dune sands. PCA variable circles (mineral constituents): (**a**) Factors F1F2; (**b**) Factors F1F3; and (**c**) Factors F1F4.

The unweathered quartz grains, present in secondary proportions in all samples, always in higher amounts than the minority quartz, show no significant correlation with the other quartz types and would be indigenous sediments, derived from aeolian erosion, deposited locally or mobilized over short distances and durations.

Thus, we could affirm the coexistence of two segments of sandy stocks: mixtures with varying proportions of sands of different origins and compositions, often constituting the entire sample but sometimes forming a specific grain size fraction of the sample. Some of them are enriched with diagenetic calcite independently of their composition and origin. These two segments are:

- Sand stocks with dominant rounded matte quartz grains, secondary unweathered grains, and minor frosted shiny quartz grains, mostly depleted in accessory minerals (garnet, tourmaline, zircon, rutile, disthene, and epidote) and oxides (magnetite and ilmenite), in addition to rock fragments.
- Sand stocks with dominant rounded matte quartz grains, secondary frosted shiny quartz grains, and minor unweathered grains, composed of garnet only as an accessory mineral with rock fragments, and the absence of oxides, micas, and feldspars.

The near absence of correlation between the petrographic and mineralogical composition and the grain size [27] suggests that, regardless of the aeolian evolution a sandy stock has undergone, it would consist of grains of various natures, deposited either without transport, close to their sources, or mobilized to varying distances from the source solely by the dominant winds, or by winds combined with minor fluvial transport. Correlatively, regardless of the transport mode responsible for the grains, they would differentiate according to the wind dynamics to form the various grain-size stocks. This lack of relationship was also observed for the dune sands of Merzouga-Tafilalet [10, 33].

6. Conclusions

Based on the results of this research, it was found that quartz, due to its high resistance to alteration, is generally the dominant mineral in all the samples studied, from a minimum of 52% to a maximum of 90%. This dominance indicates that the source of these sands may be granite or quartzite. Potassium feldspars come second, with a contribution from oxides such as magnetite and ilmenite, and sometimes as inclusions in quartz, showing the oxidation process. Values for light minerals reach a maximum of 9%, indicating that these sands have been subjected to extreme climatic conditions.

This is due to climatic factors such as heat, wind and rain. Heavy minerals were absent from the majority of sands, except in the 225 μm fraction, where their percentage reached 19%. This variability in mineralogical composition linked to the granulometric fraction suggests that granulometry influences mineralogical composition and indicates the variability of the wind regime.

Thanks to this mineralogical characterization, we have suggested that two sources of sediment were at the origin of the dune sands: a local source that provided a significant quantity of opaque ferromagnesian minerals (fraction 225 μm) and rock fragments of a sedimentary nature and iron oxides, and a distal source of quartz, limestone, and rock fragments, probably due to a sedimentary, metamorphic and igneous contribution from sedimentary rocks in neighbouring regions.

Consequently, the probable origin of these sandy deposits, which exhibit both sedimentary and volcanic signatures, can be attributed to a combination of sources. Predominantly composed of sandstones, they also contain minimally altered microgranites consisting of quartz, potassium feldspar (orthoclase), and microcline. Additionally, Hercynian and Triassic intrusions, including microgranite, microgabbro, and diabase dikes and veins, contribute to the geological composition of the deposits.

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. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The authors agree to share their research data.

Conflicts of Interest

The authors declare no conflict of interest.

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