ESTUDOS DO QUATERNÁRIO / QUATERNARY STUDIES
Nº 25, APEQ, 2025, pp. 77-88 | DOI: https://doi.org/10.30893/eq.v0i25.235

Received: February, 20th, 2025; Accepted: December, 19th, 2025

# Aeolian dynamics: mineralogical composition and source of Dakhla dune sands (Southern Morocco).

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**Abstract**

As in many arid regions worldwide, wind-driven sand transport removes large quantities of sediment from multiple sources, thereby intensifying desertification processes in southern and southeastern Morocco. In this region, desertification is particularly evident through the active movement of dune sands.The study of wind dynamics in southern Morocco seeks to elucidate the environmental conditions and geomorphological processes that drive desertification, from bedrock erosion to the transport and deposition of diverse sand deposits. In this context, the present research provides a detailed petrographic and mineralogical characterization of the Dakhla sands, enabling the identification of their provenance and transport mechanisms

The Dakhla dune sands consist primarily of quartz grains and accessory minerals, including oxides, heavy minerals, and sandstone fragments, with smaller amounts of feldspars, micas, and calcite. This mineralogical composition reflects erosion, transport, and depositional processes associated with crystalline and sedimentary formations from the Anti-Atlas and Saharan domains, which supply the study area through both hydrological and aeolian pathways.

The quartz grains of the Dakhla dune sands, accumulated predominantly by wind action, are mainly rounded and dull grains of aeolian origin. However, a significant proportion comprises glossy, abraded grains of aquatic (mainly coastal or fluvial) origin, together with angular, locally derived grains. The mineralogical associations identified three main types of sand stocks:

1) Aeolian sands - dominated by rounded, dull quartz grains enriched in accessory minerals, primarily wind-transported and of likely crystalline origin.
2) Mixed alluvial-aeolian sands - characterized by glossy, abraded quartz grains enriched in accessory minerals, resulting from alluvial transport followed by aeolian reworking, with both crystalline and sedimentary sources.
3) Coastal sands - composed mainly of glossy, abraded quartz grains poor in accessory minerals, indicative of a highly quartzose composition of coastal origin.

Overall, the results clarify the complex interplay between aeolian, alluvial, and coastal processes in shaping the Dakhla dune sands, and underscores the importance of sediment provenance analysis for assessing the evolution of desert landscapes in southern Morocco.

**Keywords:** Desertification, Mineralogical, Aeolian origin, Sandy stocks, Crystalline and Sedimentary.

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# 1. Introduction

Desertification is a global environmental challenge that affects numerous countries and requires continuous monitoring (UNCCD, 2017), as its impacts often exceed those of other land degradation processes and can seriously threaten industrial and tourism infrastructures (Karanisa *et al.*, 2021). Its occurrence and severity vary from one region to another, depending on the interactions between the natural environment and human activities (Zhang, 2018).

Resulting from a combination of climatic, anthropogenic, edaphic, and biotic factors, desertification triggers and intensifies a range of ecological, energy, food, socio-economic, and political crises. According to the United Nations Environment Programme (UNEP, 1992), this global phenomenon affects nearly one billion people, covers about 40% of the Earth's surface, and causes annual economic losses estimated at 42.3 billion US dollars.

To better understand the mechanisms underlying desertification, sedimentological and mineralogical studies are essential. The mineral composition of sands, as well as the specific characteristics of each grain, particularly the degree of rounding, allow the reconstruction of sediment transport pathways in both coastal environments (Clemens & Komar, 1988) and aeolian dune systems (Muhs *et al.*, 1997; El-Sayed, 1999). Quartz, the most widespread detrital mineral in clastic sediments (Pettijohn *et al.*, 1972), undergoes morphological modifications during erosion, transport, and deposition due to mechanical and chemical processes (Crook, 1968; Moss, 1972; Mazzullo *et al.*, 1986; Pye & Mazzullo, 1994).

The coastal regions of southern Morocco, located along the Atlantic Ocean, are characterized by the predominance of wind processes that actively shape the coastal landscape. Under the influence of powerful trade winds and a hyper-arid climate, these areas feature vast fields of dunes and particularly marked sediment mobility. Adnani's (2018) work on the Tarfaya basin highlighted the importance of wind transport in the formation and evolution of dune systems, where interactions between prevailing winds, topography, and sand deposits shape varied morphologies.

As a result, barkhanes are the most characteristic dune forms in these Atlantic regions (Elberlrhiti, 2005). Their genesis begins in coastal areas, often in close proximity to the shore, where sand, gradually dried out by the action of the wind, gives rise to embryonic forms called shields, which then evolve into fully developed barkhanes as they migrate inland.

In this context, the present study aims to examine the mineralogical characteristics and grain morphology of aeolian dune sands from the Dakhla–Aousserd region, with two specific objectives: (1) to identify and classify different varieties of quartz grains, and (2) to relate these variations to the post-sedimentary mechanical and chemical processes that define the mode of formation of these sands.

The outcomes of this study will enhance our understanding of the provenance and transport mechanisms of quartz sand grains within the Dakhla dune system. Moreover, this knowledge is essential for assessing the sedimentary dynamics and accumulation patterns of the area, which represent a potential source of environmental degradation if not properly managed. The results will support the development of an integrated management plan for the biologically rich Dakhla Bay, aimed at defining sustainable human activities compatible with the preservation of its ecological balance.

# 2. Geographical and climatic context

The study area lies between Dakhla and Aousserd (Fig. 1) in the Saharan provinces of southern Morocco. It is traversed by a northwest–southeast trunk road connecting the two towns and can be divided into two geographically distinct zones.

The first zone, located in the coastal region of Dakhla, includes both the Dakhla Bay and Peninsula. It is characterized by an ocean-moderated desert climate, which reduces annual thermal amplitude and maintains mean annual temperatures between 17 °C and 26 °C (Peyron, 2000; Sanchez & Martin, 2019). Although precipitation is scarce (less than 40 mm per year), relative humidity remains relatively high due to the persistent Atlantic trade winds. These winds strongly influence local aeolian dynamics, shaping the coastal landforms and promoting the development of extensive, mobile dune fields in continuous motion (Fontugne & Duplessy, 1981). Vegetation cover is sparse and consists of xerophytic species adapted to arid conditions typical of Saharan environments (Rognon, 1976; Barbero *et al.*, 1994).

The second zone, continental and strictly Saharan, covers the Aousserd region, situated farther inland and beyond the moderating influence of the ocean. This area experiences an extreme desert climate, with summer daytime temperatures often exceeding 45 °C, marked diurnal thermal variations, and annual rainfall below 50 mm (Benattia & Hassan, 2020). Low humidity levels and persistent hot winds reinforce aridity, severely limiting vegetation and creating harsh living conditions for local populations (Laurent & Benhammou, 2021).

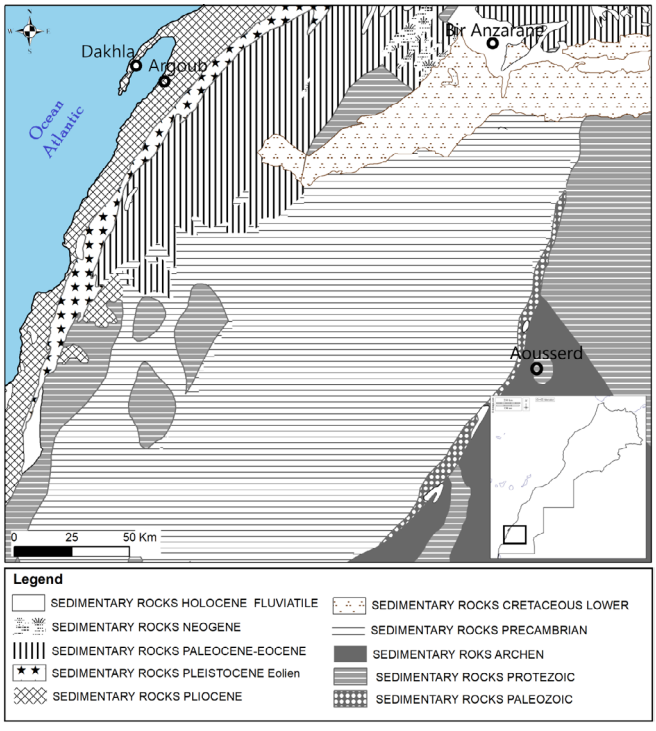


Fig. 1. Geographical framework of the study area.

The prevailing winds in the Dakhla–Aousserd region are characterized by moderate to high intensities, with mean wind speeds generally ranging between 6 and 10 m/s. Periods of strong winds exceeding 16 m/s are frequent, occurring for approximately 120 to 160 days per year, mainly during the summer season (June–August), when maximum gusts can reach 20–21 m/s (Anda, 2015).

This energetic and persistent wind regime constitutes the main driver of aeolian processes in the study area. Wind velocities frequently exceed the threshold required for sand entrainment, promoting active saltation and surface creep, and leading to continuous sediment transport and reworking. As a result, these winds strongly control dune mobility, migration rates, and sediment redistribution. They also exert a direct influence on the morphology, orientation, and spatial organization of dune forms, contributing to the development and evolution of the dune systems characteristic of the Dakhla–Aousserd area.

# 3. Geological setting

The study area is characterized by four distinct stratigraphic units, ranging from the Archean to the Cenozoic. The Archean units of the Réguibat Ridge are mainly composed of granites, migmatites, and gneisses (Villeneuve, 2008). Wind and water erosion have sculpted this ancient landscape into plateaus dissected by ravines and depressions, forming buttes and cuestas (Fig. 2) with distinct angular contours (Fabre, 2005).

Fig. 2. Hillock at the bottom of the photo, upstream from the sand deposits on the sandstone rocks.

To the south (Fig. 3), the Neoproterozoic units of the Adrar Souttouf range are represented by oxidized sandstones, quartzites, shales, orthogneisses, and granites, interlayered with basalts and tuffs (Soulaimani et al., 2004). These consolidated and allochthonous formations display a more rugged morphology than those of the Réguibat Ridge, with cuestas aligned parallel to the region's tabular structures (Michard *et al.*, 2008). Along the eastern boundary, these Neoproterozoic units rest unconformably on the thin Paleozoic cover of the ridge, composed primarily of Ordovician sandstones and quartzites (Caby & Kiénast, 2009).

The Mesozoic and Cenozoic sedimentary cover consists mainly of sandstones, conglomerates, clays, and marls deposited in shallow fluvio-lacustrine and marine environments. The high iron oxide content imparts a characteristic reddish coloration to these rocks (Beaudet *et al.*, 1967; Fabre, 2005). More resistant limestone formations locally form cliffs that delineate stepped plateaus, while quartz-rich Paleozoic and Mesozoic sandstones favor the accumulation of aeolian deposits and the development of dune systems (Theveniaut & Dallmeyer, 2009).

In the coastal region of Dakhla, the Mesozoic–Cenozoic cover is partly overlain by Quaternary sands and alluvial deposits, shaped by the combined action of aeolian and fluvial processes (Le Goff *et al.*, 2001; Caby & Kiénast, 2009).

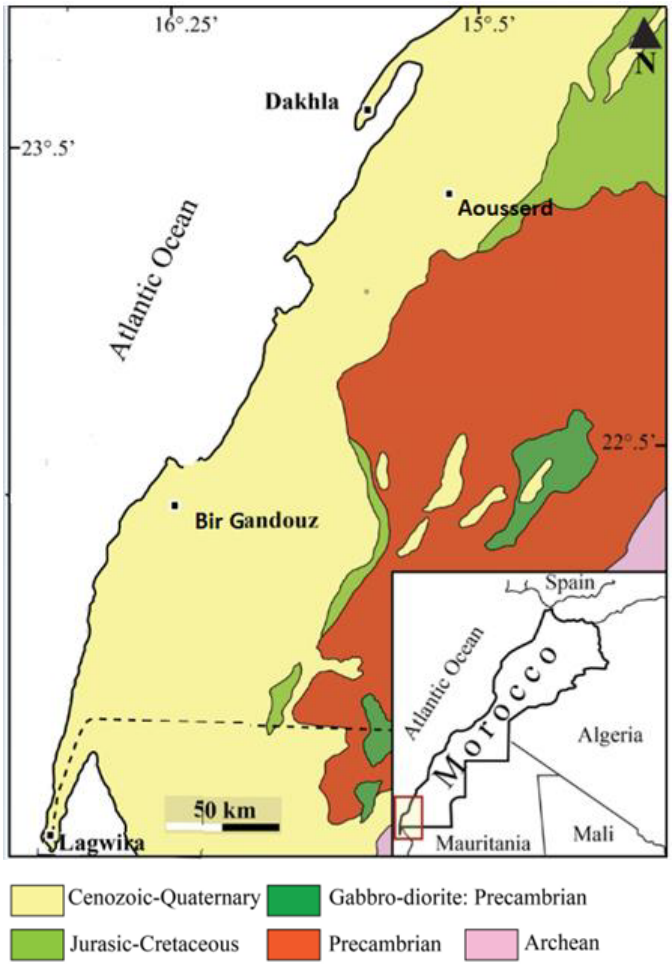


Fig. 3. Simplified regional geological map (from Saadi, 1982, modified)

# 4. Materials and Methods

Two complementary approaches were employed to study and characterize the grain size distribution and mineralogical composition of the sandy accumulations in the Dakhla region (Fig. 4).

The first approach involved fieldwork and facies observation. Sand samples were collected directly from representative dune and surrounding deposits across the study area, while the encountered and adjacent facies types were identified and described. Field activities included detailed geological surveys, facies recognition, and sampling for subsequent laboratory analyses. Each sample was stored in a labelled plastic bag to ensure traceability and prevent contamination.

A Global Positioning System (GPS) was used to record the exact locations of the sampling sites and to measure the heights of dunes relative to sea level (Table 1). The sampling sites are shown on the geological map (Fig. 5).

The second approach comprised laboratory analyses performed on the collected samples. These analyses included sedimentological, calcimetric, and mineralogical investigations aimed at determining grain size distribution, carbonate content, and mineral composition.

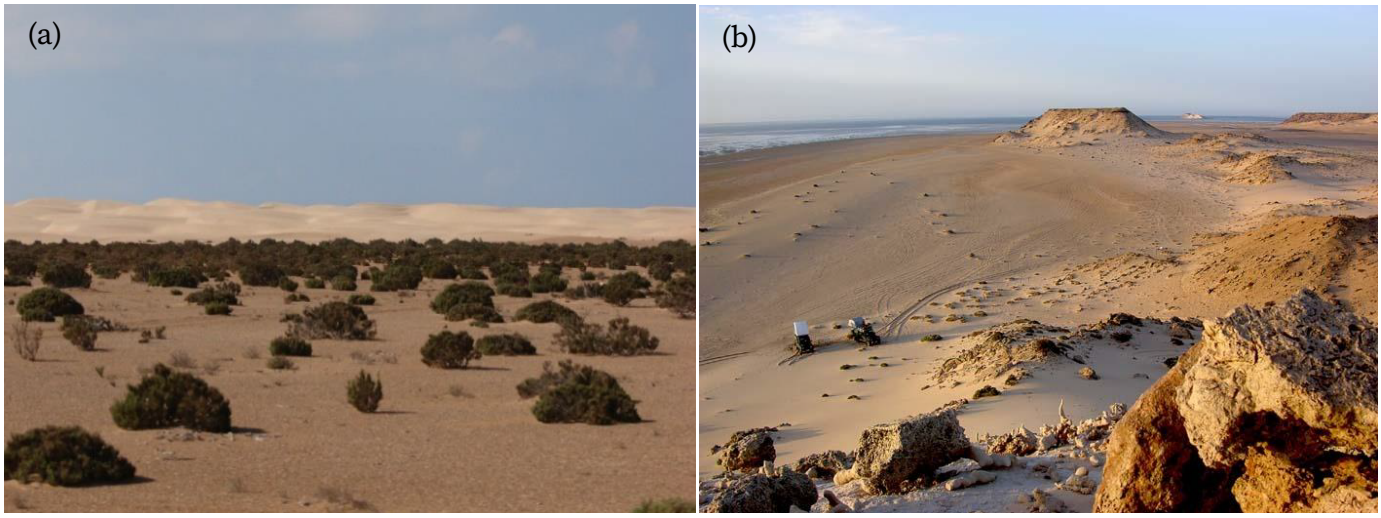


Fig. 4. (a) In the background of the photo, a whitish sand accumulation bordered by vegetation; (b) current sand dune adjacent to the beach.

**Table. 1. Dakhla-Aousserd samples coordinates.**

| Date | Sample number | Locality | Reference photos | Google Earth reference | Latitude | Longitude |
|---|---|---|---|---|---|---|
| 07-11-19 | 2 | Dakhla road towards roundabout exit | | | 23°53’33,1"N | 15°48’33,2"W |
| 07-11-19 | 3 | Dakhla road towards roundabout exit | DSC05957 to DSC05961 DSC05991 to DSC05996 | md-5 | 23°54'14.30"N | 15°43'34.14"W |
| 07-11-19 | 4 | Dakhla road towards roundabout exit | DSC05960 to DSC05973 | md-22 | 23°54'49.36"N | 15°46'37.98"W |
| 07-11-19 | 5 | Dakhla road towards roundabout exit | DSC05974 to DSC05979 | md-18 | 23°53'37.44"N | 15°40'36.17"W |
| 07-11-19 | 6 | Dakhla road towards roundabout exit | | | | |
| 07-11-19 | 7-8 | Porto Rico beach | DSC05980 to DSC05983 | md-7 | 23°28'41.56"N | 15°57'2.94"W |
| 07-11-19 | 9-10 | Hot spring | Camera infinix | md-6 | 23°54'5.86"N | 15°42'37.15"W |
| | | | | | | |
| 08-11-19 | 12 | | DSC06019 to DSC06034 | md-10 | 23°14'10.31"N | 15° 8'47.56"W |
| 08-11-19 | 13 | | DSC06055 to DSC06065 | Md-15 | 22°27'47.10"N | 14°20'44.06"W |
| 08-11-19 | 14 | | DSC06066 to DSC06068 | md-14 | 22° 0'34.66"N | 14°38'55.72"W |
| 08-11-19 | 15 | Tichla road | DSC06069 to DSC06076 | md12, md13 | 21°55'8.20"N | 14°42'8.80"W |
| 08-11-19 | 16 | | DSC06083 to DSC06092 | md-11 | 22°35'29.21"N | 14°23'22.52"W |
| 08-11-19 | 17 | | DSC06093 to DSC06097 | md-26 | 23°29'57.75"N | 15°32'59.03"W |
| 08-11-19 | 19 | PK Dakhla 148 | DSC06101 to DSC06102 | md-24 | 22°54'22.15"N | 14°44'52.07"W |
| 08-11-19 | 20 | Dakhla 128 | DSC06098 to DSC06100 | md-25 | 23°25'33.06"N | 15°25'8.71"W |
| 08-11-19 | 21 | PK Dakhla 117 | DSC06103 to DSC06112 | md-8 | 23°35'15.09"N | 15°41'8.59"W |
| 08-11-19 | 22 | Grayer el mahnak | DSC06113 to DSC06120 | md-9 | 23°33'54.11"N | 15°40'42.90"W |
| 08-11-19 | 24 | Dakhla north entrance | DSC06121 to DSC06123 | md-21 | 23°55'18.94"N | 15°45'32.55"W |
| | | | | | | |
| 09-11-19 | 28 | | | md-9 | 23°33'54.11"N | 15°40'42.90"W |
| 09-11-19 | 29 | Atittude | | md-20 | 23°53'37.18"N | 15°46'17.56"W |
| 09-11-19 | 30 | Atittude-exit | | md-2 | 23°53'45.90"N | 15°46'7.76"W |
| 09-11-19 | 31 | Attitude north | | md-3 md-4 | 23°54'3.29"N | 15°45'53.92"W |
| | | | | | | |
| 09-11-19 | 32 | Edge wall facing station | | md-19 | 23°53'36.72"N | 15°41'4.52"W |

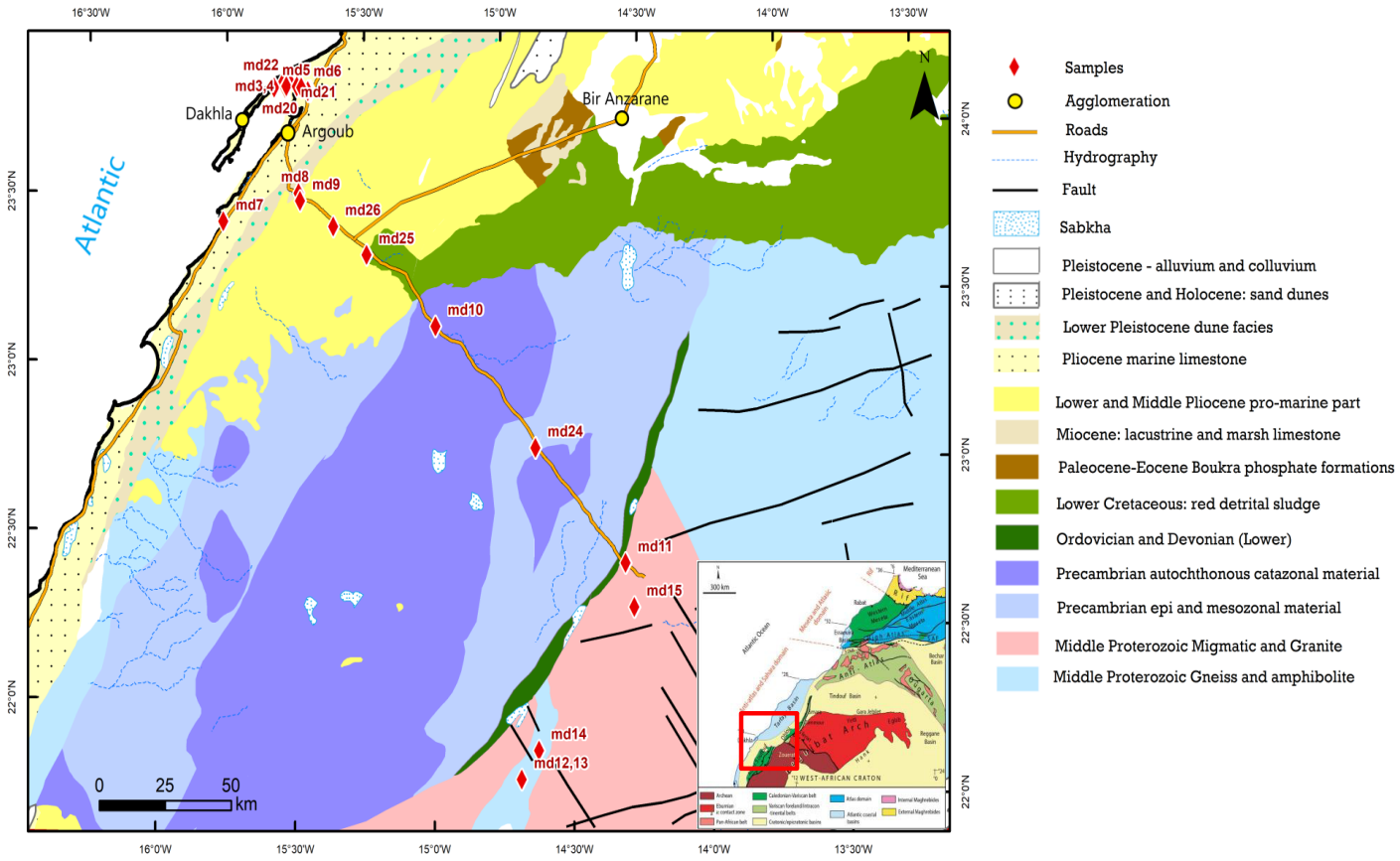


Fig. 5. Sampling sites for mineralogical and sedimentological analysis.

## 4.1. Petrographic and Morphoscopic Analysis

The petrographic and morphoscopic analyses were conducted using a binocular microscope. The observed criteria included grain color, shape, and luster, following the methodology proposed by Parfenoff *et al.* (1970). Morphoscopic examination enables the identification of the petrographic and mineralogical composition of the grains that constitute the sand deposits, as well as the statistical quantification of mineral proportions (Ribault, 1977).

For each sample, approximately 100 grains were counted from each modal fraction representative of the total sand population. Heavy minerals were separated prior to observation using bromoform (density ≈ 2.89 g/cm$^3$) to facilitate their mineralogical identification.

The analysis of the shape and surface features of detrital quartz grains aimed to infer their modes of transport and depositional history. The petrographic characterization of non-quartz grains focused on identifying their mineralogy and interpreting their provenance.

Morphoscopic types of quartz grains, together with the associated mineral categories identified in the Dakhla dune sands, were subjected to multivariate statistical analysis using Principal Component Analysis (PCA). This approach was used to explore potential correlations among petrographic and mineralogical parameters. The four principal components extracted (F1, F2, F3, and F5) explained approximately 75% of the total variance, providing a satisfactory representation of the main relationships within the dataset.

In addition to microscopic analysis, X-ray diffraction (XRD) was used to qualitatively determine the mineralogical composition of the studied sands. Portions of the dried bulk samples were ground and analyzed using an X-ray diffractometer at the CURI laboratory in Fez. Mineral phases were identified based on their characteristic diffraction peaks (2θ values).

Calcimetric analysis was employed to determine the carbonate content of the sediments. This technique measures the volume of carbon dioxide released when a known mass of sediment reacts with hydrochloric acid, providing a quantitative estimate of carbonate concentration.

# 5. Results

## 5.1. Morphoscopy and mineralogical composition

Petrographic analysis of the Dakhla dune sands, carried out using a binocular microscope, revealed a composition dominated by quartz grains (Fig. 6), representing between 70% and 90% of the total mineral fraction, with an average exceeding three-quarters of the bulk material. X-ray diffraction (XRD) results corroborate these observations, showing prominent silica ($SiO_2$) diffraction peaks, which confirm the dominance of quartz within the samples.

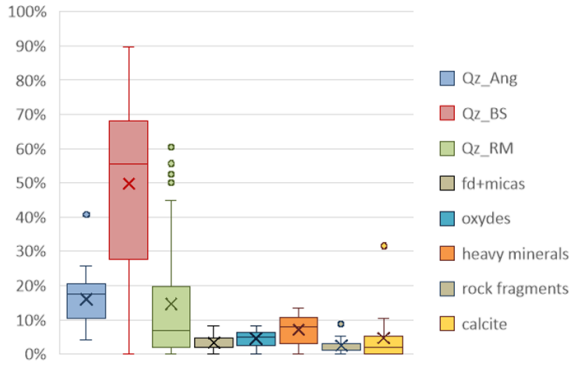


Fig. 6. Composition and proportions of quartz types and accessory mineral groups

Accessory minerals are present in smaller but significant proportions. Heavy minerals constitute up to 10% of the total assemblage, followed by oxides (≈ 8%), calcite (≈ 5%), feldspars and micas (≈ 4%), and rock fragments (≈ 3%).

Morphoscopic analysis of the quartz grains identified three distinct categories based on shape and surface appearance (Fig. 7):

1) Shiny, blunt quartz grains constitute the dominant morphoscopic type, representing between 56% and 96% of the total quartz population, with an average proportion of 75%. In some samples, however, their abundance decreases markedly, ranging from 0% to 19% (average 9%), where other types become predominant.
2) Matte, rounded quartz grains form the second major type. They can also dominate certain samples, ranging from 57% to 73% (average 66%), but in others, they appear only in minor proportions (0-15%; average 6%).
3) Unworn quartz grains occur as a secondary morphoscopic component, averaging 20% of the quartz stock. Their proportions vary between 4% (minimum) and 44% (maximum), but they never constitute the dominant population.

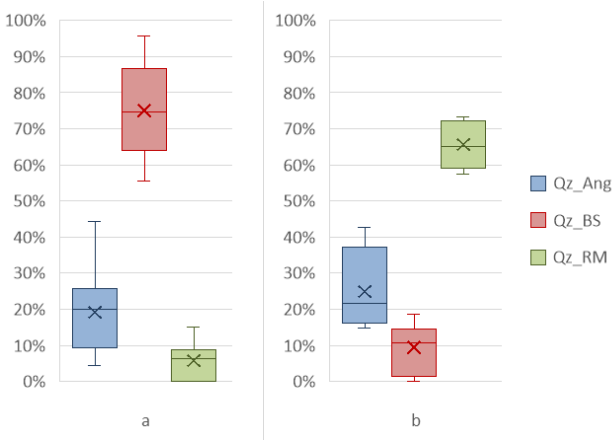


Fig. 7. Relative proportions of the three types of shapes and aspects of quartz grains in Dakhla dune sands. a) For BS-dominant samples; b) For RM-dominant samples. Qz_Ang: angular quartz grains; Qz_BS: blunt shiny quartz grains; Qz_RM: round mat quartz grains.

A few quartz grains display a slight ferruginous staining, suggesting limited post-depositional oxidation.

Quantitative analysis of the shapes and surface characteristics of quartz grains from the Dakhla dune sands reveals a segmentation of sand stocks into two principal types (Fig. 8). The majority of stocks are dominated by shiny, blunt quartz grains, whereas the minority stocks are characterized by matte, rounded grains. This distinction occurs primarily between samples, and to a lesser extent among granulometric fractions within the same sample.

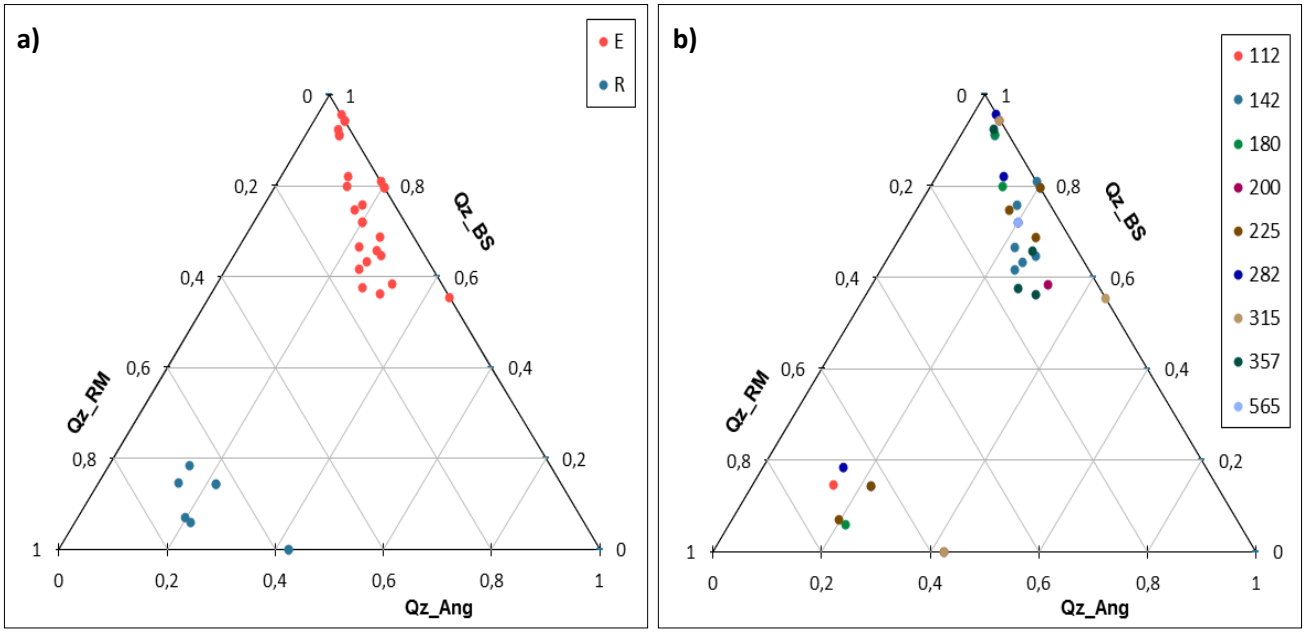


Fig. 8. Relative proportions of the three types of shape and appearance of quartz grains in the Dakhla dune sands. Qz_Ang: angular quartz grains; Qz_RM: round matte quartz grains; Qz_BS: blunt shiny quartz grains. a) By samples: E: dominant BS samples; R: dominant RM samples. b) By particle size fractions.

Sample-based discrimination indicates that the dominant stocks are composed largely of shiny, blunt grains, which may represent up to 85% of the total quartz population. In these samples, the proportion of unworn grains ranges between 3% and 40%, while matte, rounded grains constitute between 0% and 20%.

Conversely, samples enriched in matte, rounded grains display high proportions (60–80%) of this morphotype, combined with very low percentages of unworn and shiny, blunt grains, both generally below 20%.

In addition to quartz, which constitutes the main mineralogical component of the Dakhla dune sands, several accessory minerals are present, including feldspars, micas, oxides, heavy minerals, rock fragments and minor chemical calcite flakes. Feldspars, predominantly potassic, represent an average of 2.5% of the sand grains (Fig. 9), with values reaching up to 6%. Micas are absent in approximately half of the samples and occur only rarely in the remaining ones, averaging 0.5% and reaching a maximum of 3%.

Along Factor 2 (F2), a positive association emerges between zircon and tourmaline, both influenced by rock fragments (Fig. 10). However, these two minerals become antagonistic along Factor 5 (F5), indicating a divergence in their behavior under different environmental or provenance conditions.

Factor 3 (F3), accounting for approximately 14.36% of the variance, reveals two contrasting mineral assemblages. The first includes ilmenite, which correlates positively with matte, rounded quartz, unworn quartz, and calcite; the second comprises magnetite, which is inversely correlated with the first group.

Finally, Factor 5 (F5), which explains around 7.45% of the variance, shows two minor but distinct associations. The first is defined by a strong positive loading of tourmaline, which is moderately correlated with rutile and ilmenite. The second association features unworn quartz, which displays a negative correlation with the mineral group identified on F5.

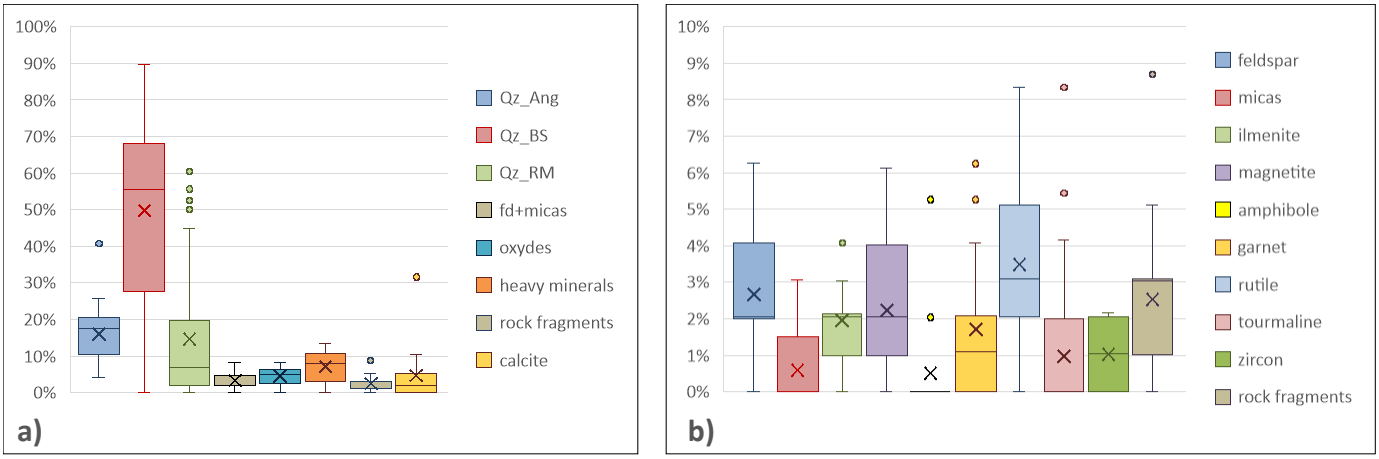


Fig. 9. Mineralogical composition of the dune sands of Dakhla: Proportions of accessory minerals. Qz_Ang: angular quartz grains; Qz_RM: round matte quartz grains; Qz_BS: blunt shiny quartz grains.

Heavy minerals and oxides constitute accessory mineral phases in the studied sands (Fig. 9), accounting on average for 6% and 4%, respectively, with maximum values of 13.5% and 8%. The main heavy minerals, listed in decreasing order of abundance (Fig. 9), are rutile (average 2.5%, maximum 6%), garnet (1.2% and 6.3%), zircon (1.2% and 2.2%), and tourmaline (1.2% and 8.3%), with amphibole occurring only as a rare component.

## 5.2. Mineralogical correlations

The segmentation of the Dakhla sand stocks is confirmed by a strong negative correlation between shiny, blunt quartz grains and matte, rounded grains, as clearly illustrated along Factor 1 (F1) of the PCA diagram (Fig. 10). The analysis also reveals a lack of correlation between unworn quartz grains and the other two morphoscopic categories.

Several mineralogical associations were identified through the PCA. The most significant, represented by Factor 1 (F1)—which explains approximately 32.29% of the total variance—shows positive correlations among the accessory minerals of the Dakhla dune sands (micas, magnetite, rutile, matte quartz, ilmenite, and potassium feldspars). These minerals correlate positively with matte, rounded quartz grains, particularly rutile and garnet, which appear to be exclusively associated with this morphotype. Consequently, these components show a negative correlation with shiny, blunt quartz grains, except for zircon, tourmaline, rock fragments, and calcite, which behave independently.

Mineralogical discrimination based on the dominance of matte, rounded quartz grains versus shiny, blunt quartz grains, as well as on grain-size fractions, was performed to explore potential correlations among the samples (Fig. 11).

The group dominated by shiny, blunt quartz grains is associated primarily with zircon, tourmaline, and rock fragments. Within this group, some samples correlate positively with Factor 2 (F2), while others show a positive correlation with Factor 1 (F1), indicating internal variability within this population.

Conversely, the group dominated by matte, rounded quartz grains is related to the negatively oriented F2 axis and is characterized by ilmenite, garnet, micas, and magnetite, which are positively correlated with one another but negatively correlated with shiny, blunt quartz grains.

Regarding grain-size fractions, no significant mineralogical correlations were observed within either group, indicating that mineral associations are independent of particle size.

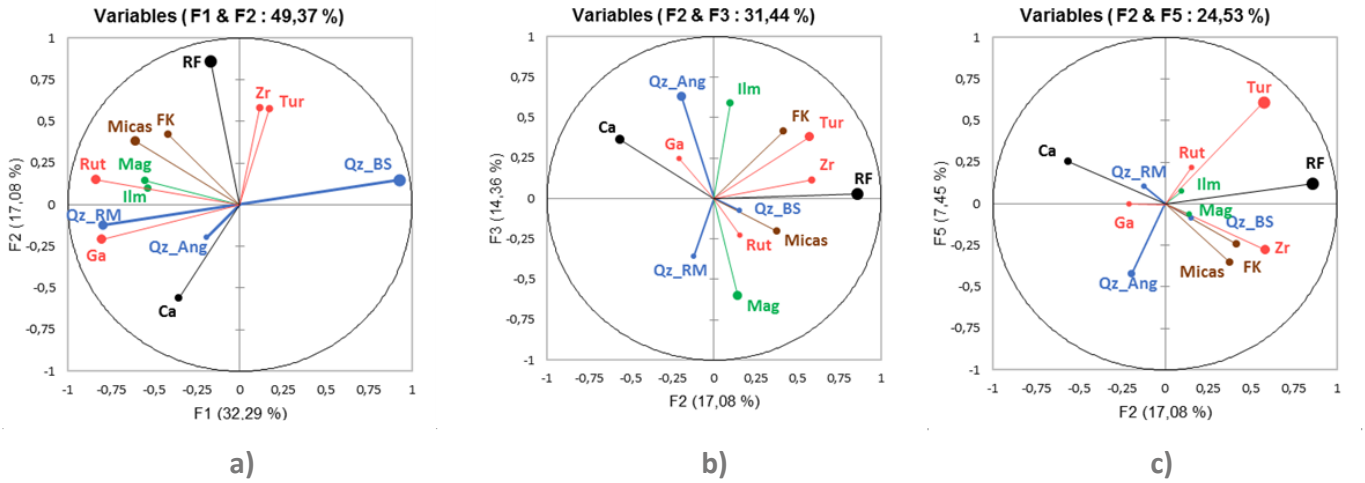


Fig. 10. PCA of the mineral constituents of Dakhla dune sands and variable circles of the PCA (mineral constituents): (a). Factors F1F2; (b). Factors F2F3; (c). Factors F2F5; Qz_Ang: angular quartz grains; Qz_RM: round, matt quartz grains; Qz_BS: blunt, shiny quartz grains; FK: potassium feldspars. Mag: magnetite; Ilm: ilmenite; Rut: rutile; Ga: garnet; Zr: zircon; Tur: tourmaline; RF: rock fragments; Ca: chemical calcite.

# 6. Discussion and interpretation

Because the Dakhla sands are primarily derived from dune systems, their origin is predominantly aeolian. However, the diversity in the shapes and surface textures of the quartz grains indicates that multiple genetic processes have contributed to their formation and evolution.

The unworn quartz grains, which occur only in minor proportions, likely represent locally derived particles that were mobilized and deposited by wind action either directly on their source substrate or in its immediate vicinity, with minimal transport or mechanical abrasion.

The matte, rounded quartz grains, which form a substantial—and in some samples, dominant—component of the Dakhla sands, likely represent particles transported exclusively by wind, or alluvial sands subsequently masked by prolonged or repeated aeolian reworking.

X-ray diffraction (XRD) analyses indicate that the alumina ($Al_2O_3$) content does not exceed 7% in most samples. This alumina is primarily derived from silicate minerals such as feldspars, micas, and heavy minerals. The oxide minerals (Fig. 7) consist mainly of magnetite (average 1.7%, maximum 5.2%) and ilmenite (average 1.8%, maximum 4.2%), whose diffraction peaks show an almost equal distribution between the two phases.

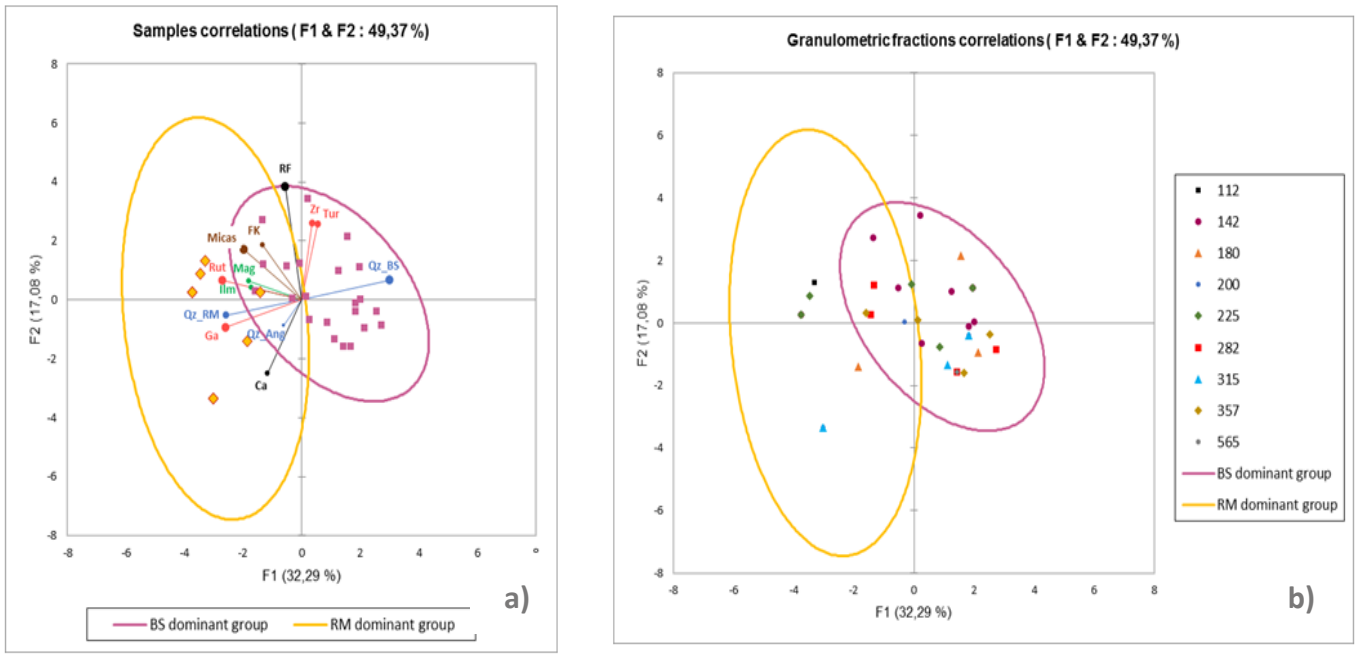


Fig. 11. PCA of the mineral constituents of the dune sands of Dakhla and PCA variable circles (mineral constituents). a. Biplot of variables/observations (samples); b. Plan of observations (grain size fractions). The ellipses represent the 95% confidence intervals of the two sand stock groups. Qz_Ang: angular quartz grains; Qz_RM: round matte quartz grains; Qz_BS: blunt shiny quartz grains; FK: Potassium feldspars. Mag: magnetite; Ilm: ilmenite; Rut: rutile; Ga: garnet; Zr: zircon; Tur: tourmaline; RF: rock fragments; Ca: chemical calcite.

In contrast, the dominance of shiny, blunt quartz grains—both in terms of their relative abundance within individual samples and the number of samples in which they prevail—suggests that a significant portion of the Dakhla sandy stock experienced fluvial or nearshore reworking prior to its aeolian remobilization. These grains were likely subjected to short-distance wind transport following their initial aquatic rounding and polishing, reflecting a complex sedimentary history involving both aqueous and aeolian processes.

Rock fragments of various colours—bright green, brown, whitish, yellowish, and greyish—occur in notable proportions, averaging 2.5% of the total grains and reaching up to 8.7% in some samples (Fig. 9). These fragments correspond to sandstone clasts, confirming a sedimentary origin for part of the material.

Calcite, of diagenetic chemical origin, is present in most samples in minor proportions, although it reaches up to 10% in two samples and 30% in one exceptional case (Fig. 6).

The matte, rounded quartz grains are typically accompanied by accessory minerals, with the exception of zircon, tourmaline, and rock fragments. This assemblage is characterized by the presence of oxides, garnet, and rutile, corresponding to a mixture of ubiquitous and metamorphic minerals according to the classification of Parfenoff et al. (1970). The source rocks of this assemblage likely correspond to Precambrian crystalline massifs and to formations from the Saharan and Anti-Atlas domains, as well as Cretaceous detrital deposits.

Altogether, these characteristics indicate that the Dakhla dune sands are predominantly of aeolian origin, incorporating reworked alluvial sediments and grains transported over long distances by wind erosion (Fig. 12).

tion. In contrast, the accessory-mineral–enriched subgroup, probably of mixed crystalline and sedimentary origin, likely corresponds to alluvial sands that were subsequently reworked by wind over limited distances.

The unworn quartz grains, which occur as a secondary component in all samples—always more abundant than the minor quartz types and showing no significant correlation with the other categories—are interpreted as autochthonous sediments. These grains are likely derived from wind erosion of local outcrops and were deposited in situ or transported only short distances before deposition.

These observations suggest the coexistence of three distinct sand-stock assemblages, each representing a mixture of sands of different origins and compositions. These assemblages generally coexist within the same sample, though in some cases they are confined to a specific granulometric fraction. Some samples also contain diagenetic calcite enrichment, which appears to be independent of grain composition or origin.

The three main sand-stock assemblages identified are:

- Assemblage 1 – Sands dominated by matte, rounded quartz grains, with secondary unworn and minor shiny, blunt grains, enriched in rutile, garnet, potassic feldspars, micas, magnetite, and ilmenite.

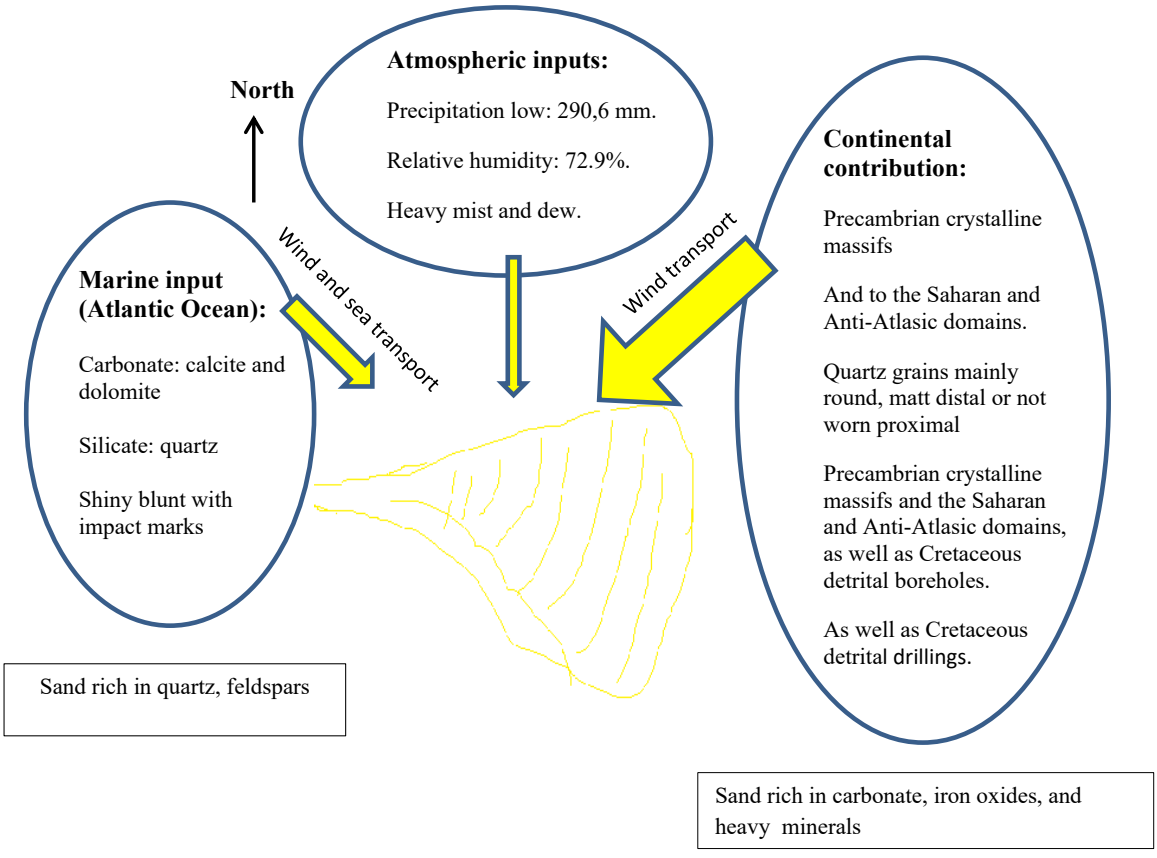


Fig. 12. Inputs leading to the formation of the dakhla dune sands. The arrows indicate the direction and thickness of the contribution.

In contrast, the shiny, blunt quartz grains are associated with the lowest concentrations of accessory minerals. When accessory minerals are present in greater abundance, these grains tend to be accompanied by zircon, tourmaline, rock fragments, potassium feldspars, and micas. Consequently, this population can be divided into two subgroups: one depleted in accessory minerals and another enriched in them.

The accessory-mineral–depleted subgroup is interpreted as being derived from beach sands that were reworked, sorted, and washed by wave action, before undergoing short-distance aeolian remobiliza-

- Assemblage 2 – Sands dominated by shiny, blunt quartz grains, with secondary unworn and minor matte, rounded grains, enriched in zircon, tourmaline, rock fragments, potassic feldspars, and micas.
- Assemblage 3 – Sands composed mainly of unworn quartz grains, with low accessory-mineral content, corresponding to autochthonous aeolian sediments derived from local erosion and short transport.

The first two mineral associations consist of a mixture of ubiquitous and metamorphic minerals, suggesting a heterogeneous prove-

nance. These sands likely received contributions from Precambrian and Proterozoic formations, including the Réguibat Shield and the Mauritanides Belt, both characterized by metamorphic and granitic lithologies. The detrital material was probably derived from these ancient terranes and transported over considerable distances under the combined influence of fluvial and aeolian processes, leading to reworking and rounding of quartz grains.

On the western flank of the Anti-Atlas, additional inputs may have originated from metamorphic sedimentary formations, further contributing to the mineralogical diversity observed in the Dakhla sands.

The western outcrops of the Anti-Atlas, composed of Paleozoic metamorphosed sedimentary rocks, together with the Precambrian metamorphic units exposed in the western Anti-Atlas and occupying part of the Oued Drâa Basin, also represent a potential source for the Dakhla dune sands.

The sand assemblages dominated by shiny, blunt quartz grains, with secondary unworn and minor matte, rounded grains, are depleted in accessory minerals. This mineralogical depletion indicates a low contribution from crystalline formations and a predominantly detrital, quartz-rich input. Such material likely originates from multiple sources, both distal and proximal, and has been influenced by the combined action of fluvial, marine, and aeolian processes.

The near absence of correlation between petrographic and mineralogical composition and grain size suggests that, regardless of the stage of aeolian evolution, each sandy deposit comprises grains of diverse origins. These grains may have been deposited directly near their source areas or transported varying distances by wind alone or by winds acting together with fluvial or wave processes.

Consequently, the textural differentiation of the Dakhla dune sands appears to be primarily controlled by wind dynamics, rather than by source composition. A similar lack of correlation between grain-size distribution and mineralogical composition has been documented in the Merzouga–Tafilalt dune fields (Harchane *et al*., 2024), reinforcing the interpretation of multi-source aeolian reworking across southern Morocco.

Comparative studies of other Moroccan desert regions provide valuable insights into the provenance of dune sands and their mineralogical diversity.

According to Boudad *et al.* (2004), the sands of the Tafilalet region display a volcanic influence, marked by the presence of augite and other volcanic minerals derived mainly from Triassic basalts intersected by the Oued Ziz near Foum Zaabel. This volcanic contribution may also originate from intrusive bodies in the High Atlas, such as the one at Foum Tillicht. In the same study, metamorphic minerals (12%) ranked third after ubiquitous minerals (26%), reflecting inputs from Paleozoic formations exposed by faulting in the High Atlas, as well as from metamorphic rocks formed by Jurassic intrusions.

Similarly, Adnani *et al.* (2016), investigating sands from the Erfoud region, demonstrated that these deposits are potentially fed by Quaternary, Cretaceous, and Viséan formations composed mainly of red sandy silt, limestone, marl, sandstone, shale, and siliceous–ferruginous conglomerates.

In a later study, Adnani (2018) analyzed megabarchan dune sands using satellite imagery and identified a heterogeneous mineralogical composition, including mafic minerals, carbonates, and quartz. This mineralogical diversity was interpreted as evidence of multiple sediment sources, a conclusion further supported by granulometric and morphoscopic analyses of the quartz grains.

In addition, Ali *et al.* (2014) reported that Meso–Cenozoic formations located in the Khaoui Nâam (Aouedri), Oum Fatma, and Chebika catchments—comprising Cretaceous to Pliocene subarkosic sandstones—are particularly rich in carbonate arenites. These formations are significantly enriched in feldspar-, garnet-, calcite-, and dolomite-bearing grains, as well as yellow- and red-hued rock fragments.

Finally, very fine heavy minerals such as hematite, ilmenite, magnetite, ulvöspinel [$Fe_2TiO_4$], and pyroxenes are known to derive predominantly from metamorphic and igneous rocks, though they may also occur in sedimentary formations rich in banded iron layers or coarse detrital deposits (Hurlbut & Klein, 1977).

# 7. Conclusions

The study of the Dakhla dune sands has provided a detailed understanding of their mineralogical and petrographic composition, revealing the origin of the sand stocks and the transport mechanisms responsible for their accumulation. The aeolian nature of these deposits was confirmed through petrographic observations and supported by detailed granulometric analyses.

From a mineralogical perspective, the Dakhla dune sands are dominated by quartz grains, representing on average more than 75% of the total assemblage. The remaining fraction consists mainly of oxides, heavy minerals, sandstone fragments, feldspars, and micas, while diagenetic calcite occurs sporadically, reflecting secondary chemical processes. Silts and clays are rare or absent due to the deflational action of wind.

Petrographically, the quartz grains display three main morphoscopic types:

1. Bright, rounded grains of predominantly aquatic (coastal or fluvial) origin,
2. Matte, rounded grains of primarily aeolian origin, and
3. Angular, unworn grains of local or autochthonous origin.

Correlation analyses revealed several significant relationships between the petrographic and mineralogical constituents of the Dakhla dune sands. Strong positive correlations were identified between matte, rounded quartz grains and minerals such as rutile, garnet, potassic feldspars, micas, magnetite, and ilmenite, reflecting an aeolian–crystalline provenance. Conversely, bright, rounded quartz grains show positive correlations with zircon, tourmaline, rock fragments, and potassic feldspars, consistent with mixed fluvial and coastal origins. Negative correlations between these groups indicate distinct source areas and transport histories.

Based on these correlations, three main sand-stock assemblages were distinguished:

- Aeolian–crystalline sands – dominated by matte, rounded quartz grains, with secondary unworn grains and minor bright grains, enriched in rutile, garnet, potassic feldspars, micas, magnetite, and ilmenite. Their transport is mainly aeolian, and their provenance is likely crystalline.
- Alluvial–mixed sands – dominated by bright, rounded quartz grains, with secondary unworn and minor matte grains, enriched in zircon, tourmaline, rock fragments, feldspars, and micas. These sands are of mixed crystalline and sedimentary origin, with fluvial transport preceding aeolian reworking.

- Coastal–quartzose sands – composed mainly of bright, rounded quartz grains, depleted in accessory minerals, and representing coastal deposits reworked by wave action and subsequently remobilized by wind.

Regardless of their initial provenance, all sand stocks were ultimately accumulated through aeolian dynamics, which acted as the dominant transport and depositional agent. This process led to the formation of well-developed dune complexes, characterized by distinct granulometric fractions: very fine (63–100 µm), fine (100–180 µm), and fine to medium (180–350 µm or more) (Harchane *et al.*, 2024).

Preliminary grain-size analyses identified three characteristic distributions: a minor unimodal, a dominant bimodal, and a polymodal pattern (Harchane *et al.*, 2024). Importantly, no significant correlation was observed between grain-size fractions and mineralogical or petrographic composition, indicating that the mineral origin of the sand stocks and their mode of transport are independent of their aeolian evolution.

# Acknowledgements

This work was supported by the *Académie Hassan II des Sciences et Techniques*. Special thanks are due to the team at the *Laboratoire des Géo-Ressources et de l'Environnement* in Fez, and to the technicians in the Geology and Chemistry laboratories at the *Faculté Polydisciplinaire de Taza*. We also wish to express our gratitude to the staff of the Fez Innovation Center at Sidi Mohamed Ben Abdellah University for their invaluable collaboration and support. Finally, we thank the anonymous reviewers for their insightful comments, which helped improve the manuscript.

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