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Origin, Source, Composition and Transport Pathways of Sand Dune (A Case Study: Garmsar Dune Fields)

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ABSTRACT

In arid environments dominated by dune fields, the form, alignment, and aeolian characteristics of sand dunes provide critical insights into their origin, sediment sources, and transport pathways. This study assesses the sedimentological characteristics of the Garmsar desert dunes to identify these key parameters. Surface sand samples were collected across a representative distribution within the Garmsar dune fields. Sediment characterization was performed using dry sieving for particle size analysis, thin-section microscopy, and X-ray diffraction (XRD) for bulk mineralogy. The results demonstrate that dune form and alignment effectively record the strong wind directions in the region. The mean sand size ranges from 187 to 345 μm (medium to very fine sand), with sorting coefficients between 1.556 and 1.779 (moderately to moderately well-sorted). These findings suggest that the sand has undergone relatively short-distance transport from its source. Mineralogical data indicate that the dunes are primarily composed of carbonate and volcanic minerals. Consequently, the primary sand origin are identified as the Upper/Lower Red Formations and the Qom Formation in the Kohe Sorkh area, with sediment transported via the Shur River in the northwest. Based on grain size characteristics, the presence of rock fragments, and mineralogical composition, it is concluded that the sediments are predominantly derived from local sources.

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1. Introduction

Dune fields in arid and semi-arid regions typically form part of local to regional scale sand transport systems, which comprise source areas, transport pathways, and depositional sinks (Lancaster *et al*., 2015). Sand dune formation occurs due to a combination of sediment supply (Pye and Teswar, 2008), sufficient wind strength (Watson, 1989; Baas et. al., 2022), reduced vegetation cover (Hess and Simpson, 2006), or extreme dominance of one of these factors.

A general concept emerging from studies on sand dunes is that the degree of activity of many dunes is only indirectly a function of climate. But according to Mabbott, the formation and expansion of many sand dunes requires sand sources, or in other words, a supply or access to sediment (Mabbutte. 1977). Therefore, the degree of dune activity may not be related to moisture balance per se, but rather to the effect climate has on supplying new sediment from fluvial or lacustrine sources (Muhs *et al*., 1995; Lancaster and Tchakerian, 1996; Tchakerian and Lancaster, 2002; Goździk *et. al.*, 2025).

Another concept that has emerged in the sand dune studies is the presence of distinct sand transport pathways. Aeolian sand transport pathways that extend over long distances and cross basins, topographic obstacles or major drainages have been recognized by geomorphologists in many of the world's deserts in the past few decades (Fryberger and Ahlbrandt, 1979; Muhs *et al*., 2003; Mashhadi *et. al.*, 2019; Goździk *et. al.*, 2025). Zimbelman *et al*. (1995) recognized two pathways of sand transport through topographic basins by analysis of dune geomorphology in the field and on Landsat imagery. Clarke and Rendell (1998) recognized both of the sand transport pathways identified by Zimbelman *et al*. (1995) and added a third. Lancaster and Tchakerian (1996) expanded on the sand transport pathway concept and also discussed paleoclimatic aspects of sediment supply.

Analysis of the mineralogy, textural, and compositional parameters (Lancaster & Tchakerian, 1996; Wang *et al*., 2002; Harchane, 2025) of aeolian sands can provide valuable information on sand source environment, the mode and pathways transport of transport, and the origin of aeolian sand. In most cases, the mineralogy of sediments reflects the nature of the source rock, while textural parameters mainly indicate the mode of transport and the energy conditions of the transport environment (Friedman, 1961; Muhs *et al*., 2003).

This paper investigates the both morphological and sedimentological characteristics of sand dunes in the Garmsar deserts in order to assess wind direction, transport pathways, and sand sources. Therefore, a combination of field observations, thin-section microscopy, particle size analysis, and X-ray Diffractometry (XRD) methods was used in this study.

2. Materials and methods

2-1. Geographical Location and General Geological Characteristics of Study Area

The study area is located beside the Varamin-Garmsar Road (south of the road), and at a distance of about 34 km from the Garmsar city. The approximate location of the area is between 51°. 57. 43̋ to 51°. 59́. 8̋ East longitude and from 35°. 10́. 22̋ to 35°. 8́. 57̋ North latitude (Figure1). Semnan Province is located in the southern domain of Alborz Height and at the northern margin of the Great Desert; hence, this province belongs to two structural flats of Alborz (central) and Central Iran in terms of geology. In the north, the Semnan Fault is considered as the separating line between Alborz and Central Iran, whereas the Attari Fault, 30km east of Semnan, is introduced as the border between these two zones in another study. The Semnan and Attari faults are two important tectonic features that pass through the northern parts of Semnan Province in the northeast-to-southwest direction. Regional data in particular, geological specifications of areas located in the north (Alborz) and south (Central Iran) of the

Semnan and Attari faults—indicate that there are no significant geological differences between the northern and southern parts of the province; in other words, the Alborz part of Semnan Province represents marginal folds of Central Iran (Aghanabati, 2004). The most important formations that are outcropped in the area, and whose sedimentology and stratigraphy are more important consist of the Lower Red, Qom, Upper Red, and Hezar–Dareh formations and the existing deposits. In general, vegetation growth is slow and difficult in the studied area and surrounding regions due to dry climate and soil composition (salinity); only those plants can be grown in this area that are resistant to salinity and dryness, and compatible with desert. These plants consist of the *Haloxylon* and *Tamarix* species (a number of them are planted in the area).

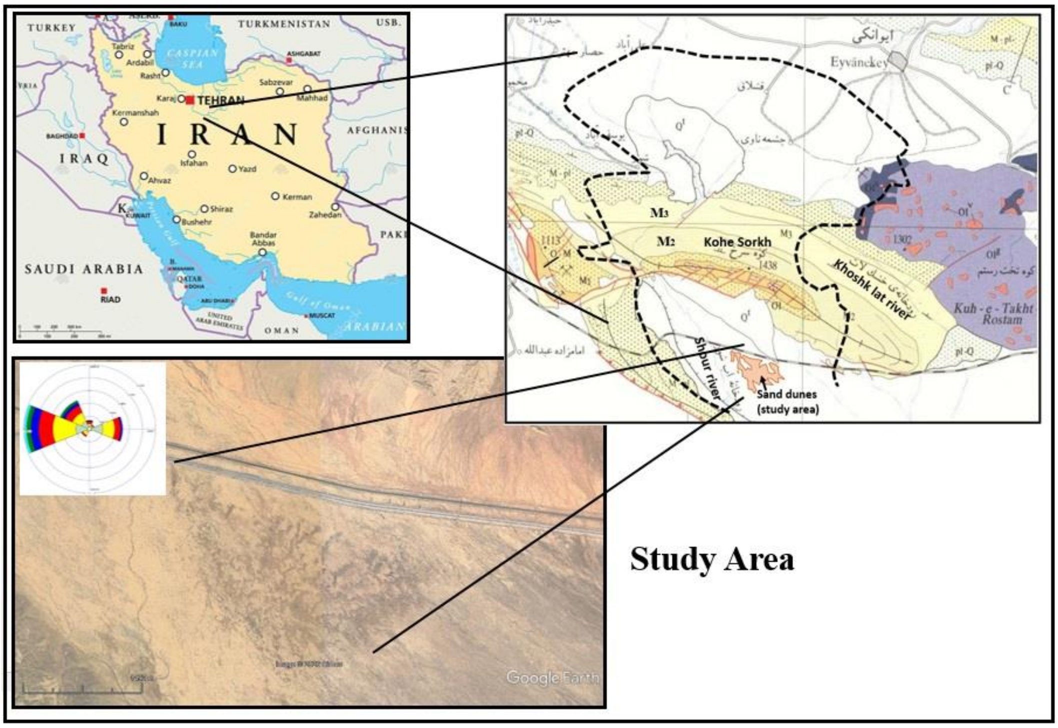


Figure 1. Geographical location of the studied area and outcropped formations

2-2. Methodology

Three complementary approaches were employed to characterize the grain-size distribution and mineralogical composition of the sand dune accumulations in the Garmsar Desert.

The first approach involved remote sensing and desk-based analysis, encompassing the interpretation of satellite imagery to assess dune morphology and identify prevailing wind directions. In this phase, multi-annual anemometric data from the Garmsar synoptic station were processed to construct the resultant wind rose.

The second approach comprised systematic fieldwork and geomorphological observation. Sand samples were collected from representative dunes across the study area, while the characteristics of both the sampled and adjacent landforms were documented. Field activities included detailed landform surveys and rigorous sampling protocols for subsequent laboratory analyses. To ensure sample integrity and minimize potential contamination, each specimen was stored in a sealed, labelled plastic bag.

The third approach consisted of laboratory analyses conducted on the collected samples.

These investigations focused on sedimentological and mineralogical parameters to determine grain-size distribution and mineralogical composition.

Particle-size analysis was performed on all samples via dry sieving (Anderson, 2004), with statistical parameters (e.g., mean size, sorting) calculated using the Gradistat software (Blott *et al*., 2001).

Furthermore, X-ray diffraction (XRD) was utilized to qualitatively determine the mineralogical composition of the bulk sand samples. Aliquots of the dried samples were pulverized and analyzed using an X-ray diffractometer. Mineral phases were identified based on their characteristic diffraction peaks (2θ values).

3. Results and discussion

3-1. Morphology of sand dunes

The morphology of sand dunes in the Garmsar desert encompasses a range of common types, primarily categorized as crescentic dunes. These can be further subdivided into two distinct forms: the developmental sequence from pre-barchan to barchan, and transverse dunes (Figure 2).

Figure 2. Satellite image showing Barchan and transverse dunes in the Garmsar dune field (Source: Google Earth)

3-2. Analysis of sand dunes morphology and determination of wind direction

The alignment and morphology of sand dunes are very useful critical indicators for determining wind direction and regimes (Zhenda, 1984). Consequently, this study employed dune elongation and form as criteria to analyze sand-transporting wind patterns. Satellite imagery analysis indicates that erosive winds predominantly originate from the west and northwest (Figure 2). These findings are corroborated by anemometer data, which show that both erosive and formative winds frequently follow westerly and northwesterly directions (Figure 3).

3-3. Analysis of statistical parameters of sand dune particles

Statistical parameters of particles, including grain size and sorting characteristics-specifically fining and improved sorting trends along transport pathways-provide insights into potential sediment sources and transport pathways. The distribution percentages and calculated statistical parameters are summarized in Tables 1 and 2.

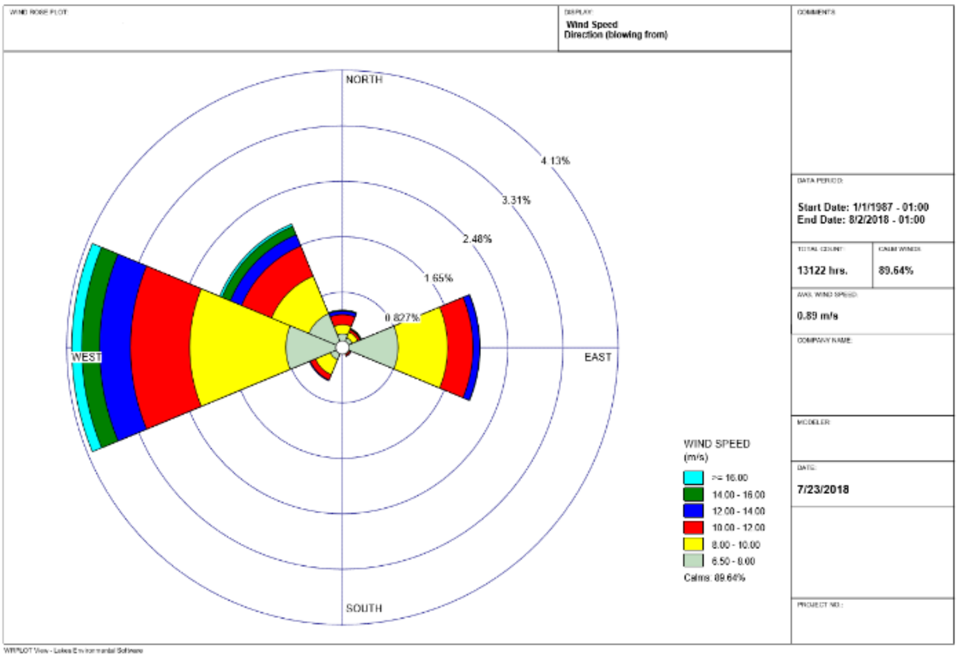


Figure 3. Annual storm rose diagram for Garmsar station, near the study

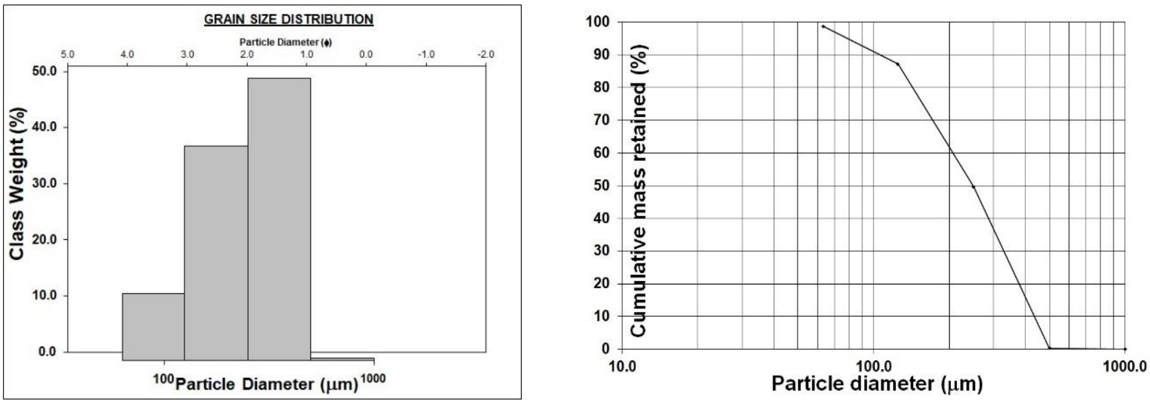
Table 1. Percentage distribution of Particle size in microns

Grain size (µ) / Samples	>2000	2000-1000	1000-500	500-250	250-125	125-62.5	<62.5=Pan	Total
1	00.0	00.0	0.37	49.32	37.49	11.56	1.26	100
2	00.0	00.0	0.22	20.28	63.68	15.08	0.74	100
3	00.0	00.06	5.64	59.29	26.60	7.13	1.28	100
4	00.0	00.04	3.37	56.76	26.95	10.11	2.77	100
5	00.0	00.12	9.42	75.40	8.89	4.85	1.32	100

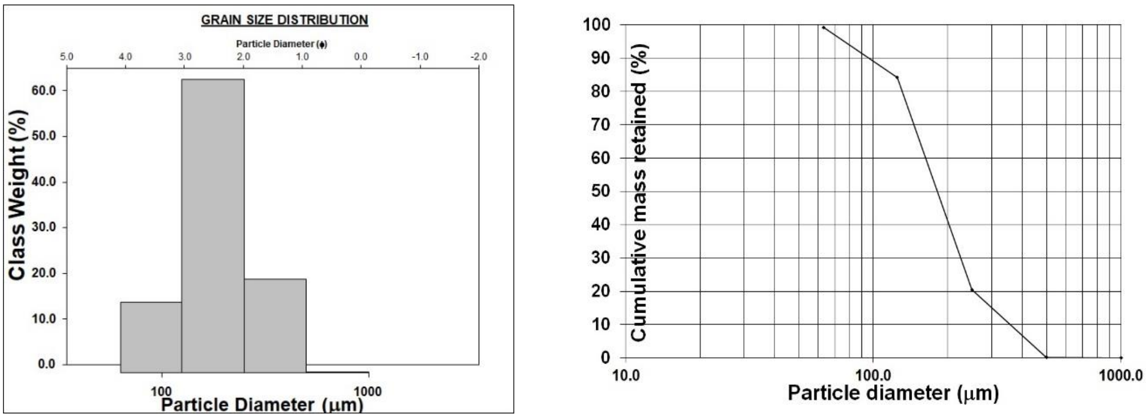
Table 2. Statistical analysis and its description on samples (Folk and Ward, 1957)

Samples	Mean grain size (µ)	Mean grain size	Median (µ)	Sorting (µ)	Sorting	Skewness(µ)	Skewness	Kurtosis(µ)	Kurtosis
1	236.5	Fine Sand	248.6	1.729	Moderately	-0.212	Fine Skewed	0.898	platykurtic
2	187.8	Fine Sand	181.3	1.602	Moderately Well	0.058	Symmetrical	1.291	Leptokurtic
3	272.0	Medium Sand	297.2	1.716	Moderately	-0.292	Fine Skewed	1.013	Mesokurtic
4	254.3	Medium Sand	283.1	1.779	Moderately	-0.351	very fine	0.961	Mesokurtic
5	344.7	Medium Sand	344.7	1.556	Moderately Well	-0.126	Fine Skewed	1.681	Very Leptokurtic
Average	259.1		270.9						

Analysis of grain size parameters reveals that the mean particle size across all samples ranges from medium to very fine sand, based on the Wentworth scale (Figure 4). Average grain sizes vary between 187.8 and 344.7 µm. Sorting coefficients range from 1.556 to 1.776, indicating that the majority of the sands are moderately to moderately well-sorted (Figure 4). Furthermore, the skewness values range from very fine-skewed to symmetrical.



Sample 1



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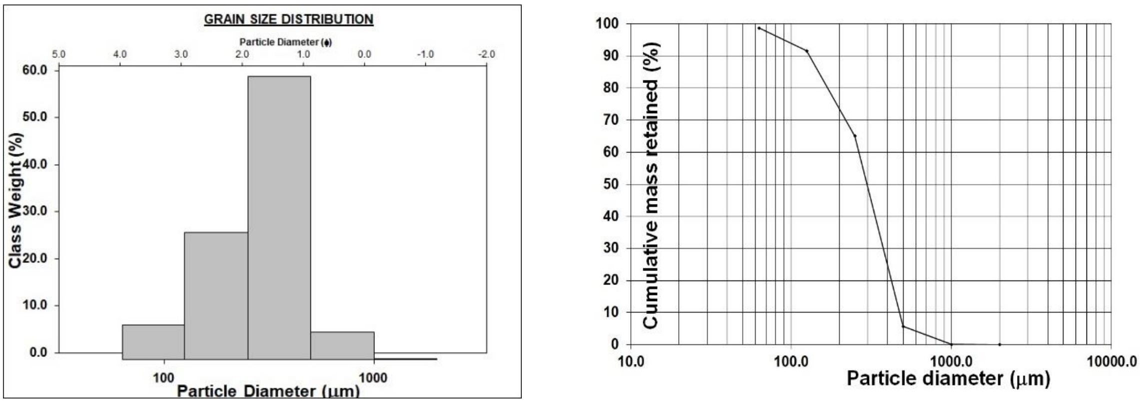
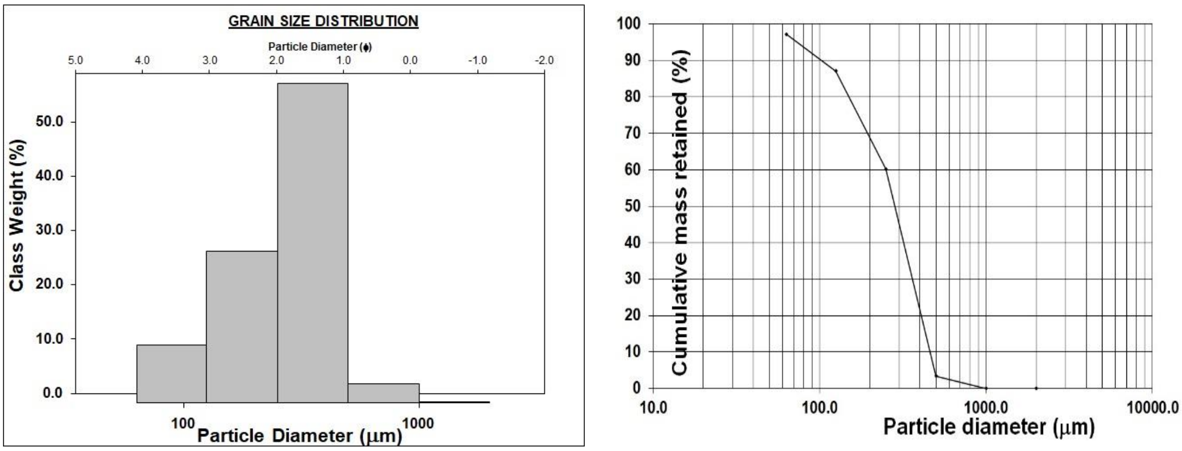
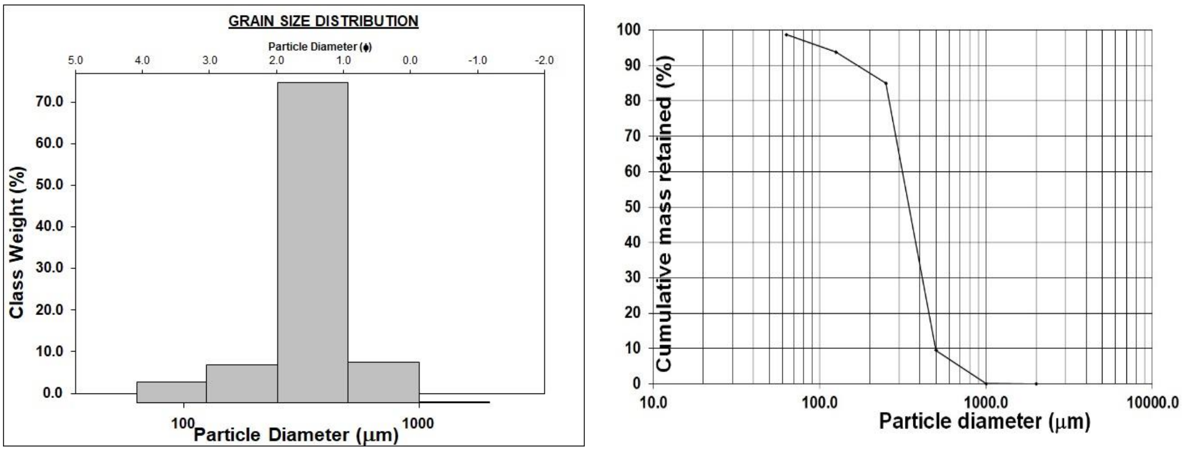


Sample 3

Figure 4. Particle size distribution and cumulative diagram for sands from each typical form dunes



Sample 4



Sample 5

Figure 4. Continued

3-4. Mineralogy

All sand-dune samples collected from the study area can be divided into two compositional groups: carbonate and volcanic (Figures 5 and 6). The silica and carbonate contents shown in the X-ray diffraction (XRD) patterns also support this classification (Figure 7).

The first group consists of carbonate components, including intracalcite particles (such as the mud carbonate particle shown in Figure 5A) and biocalcite. Although the crushed nature of the biocalcite particles prevents precise identification, they appear to include fragments of bryozoans (Figures 5J and 6E), as well as foraminifera and brachiopod fossils (Figure 5A).

The second group consists of volcanic components, with a much higher abundance of quartz than plagioclase (Figures 5 and 6). In some cases, plagioclase crystals display twinned structures, such as albite twinning in Figure 6K; however, in other cases, twinning is not observable because of weathering (Figures 5H, 5F, 5E, and 6B). In addition, fragments of wood were observed in some samples (Figure 5H).

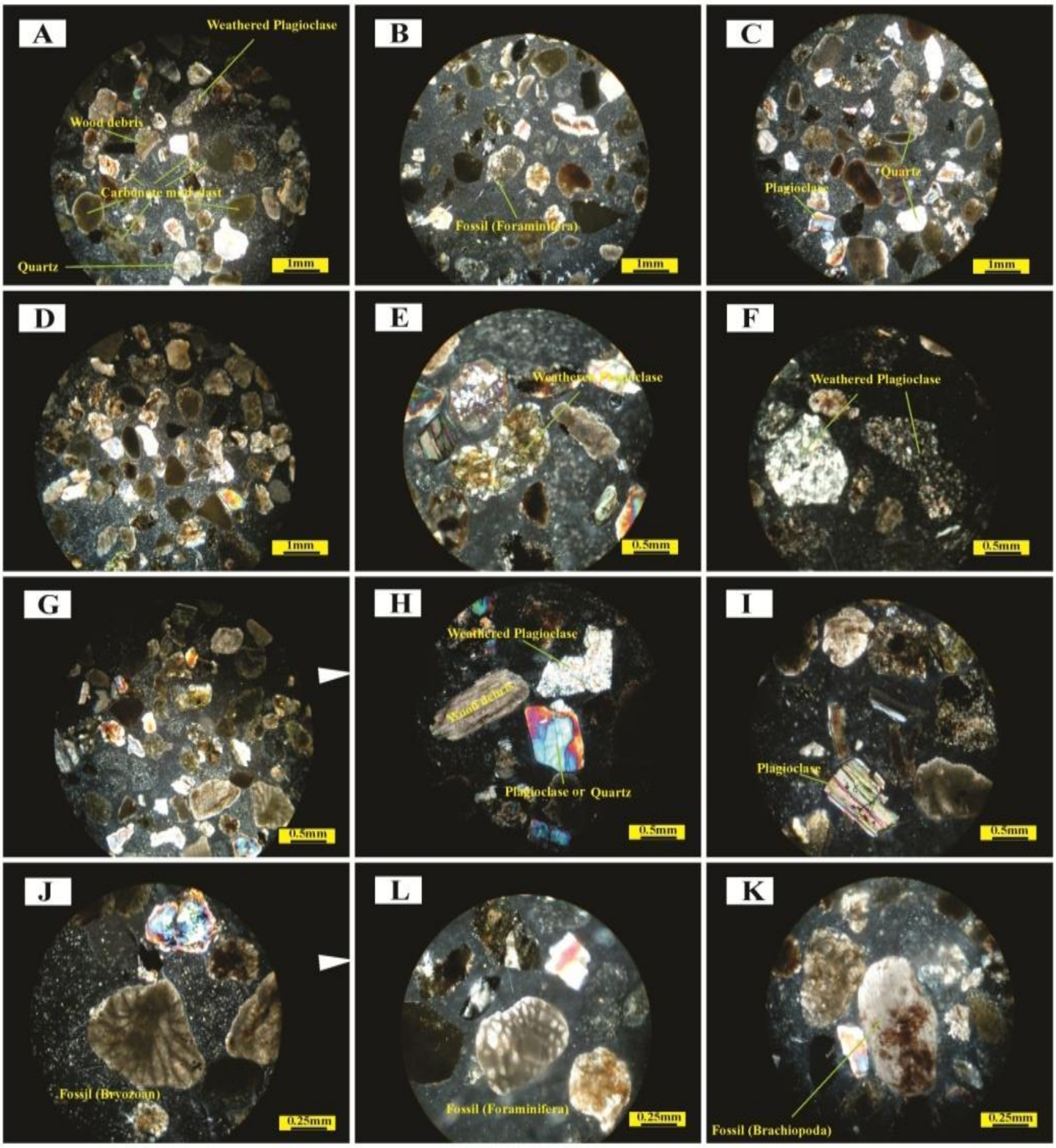


Figure 5. Samples of thin-section images (under polarizing light) determining some components

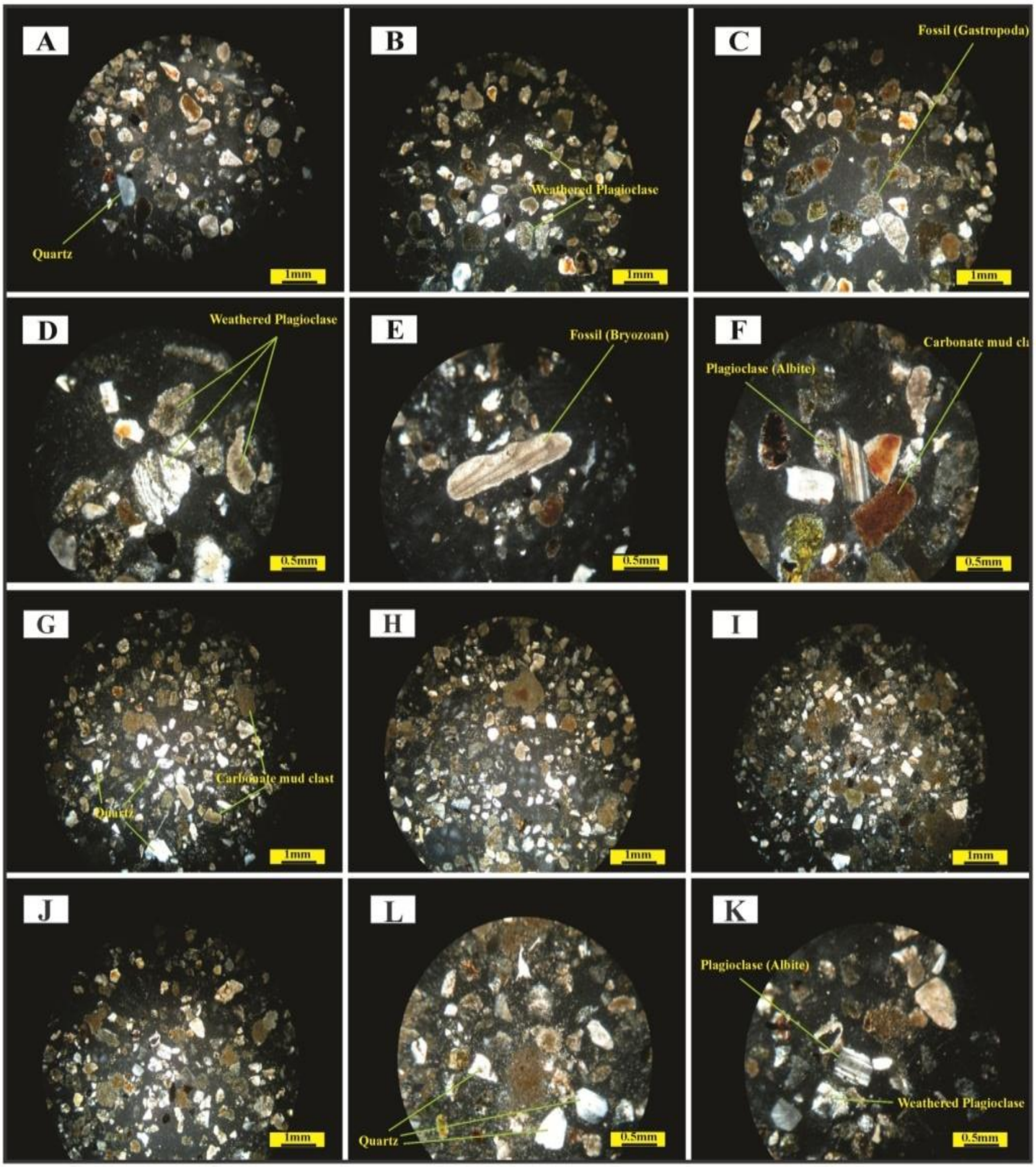


Figure 6. Samples of thin-section images (under polarizing light) determining some components

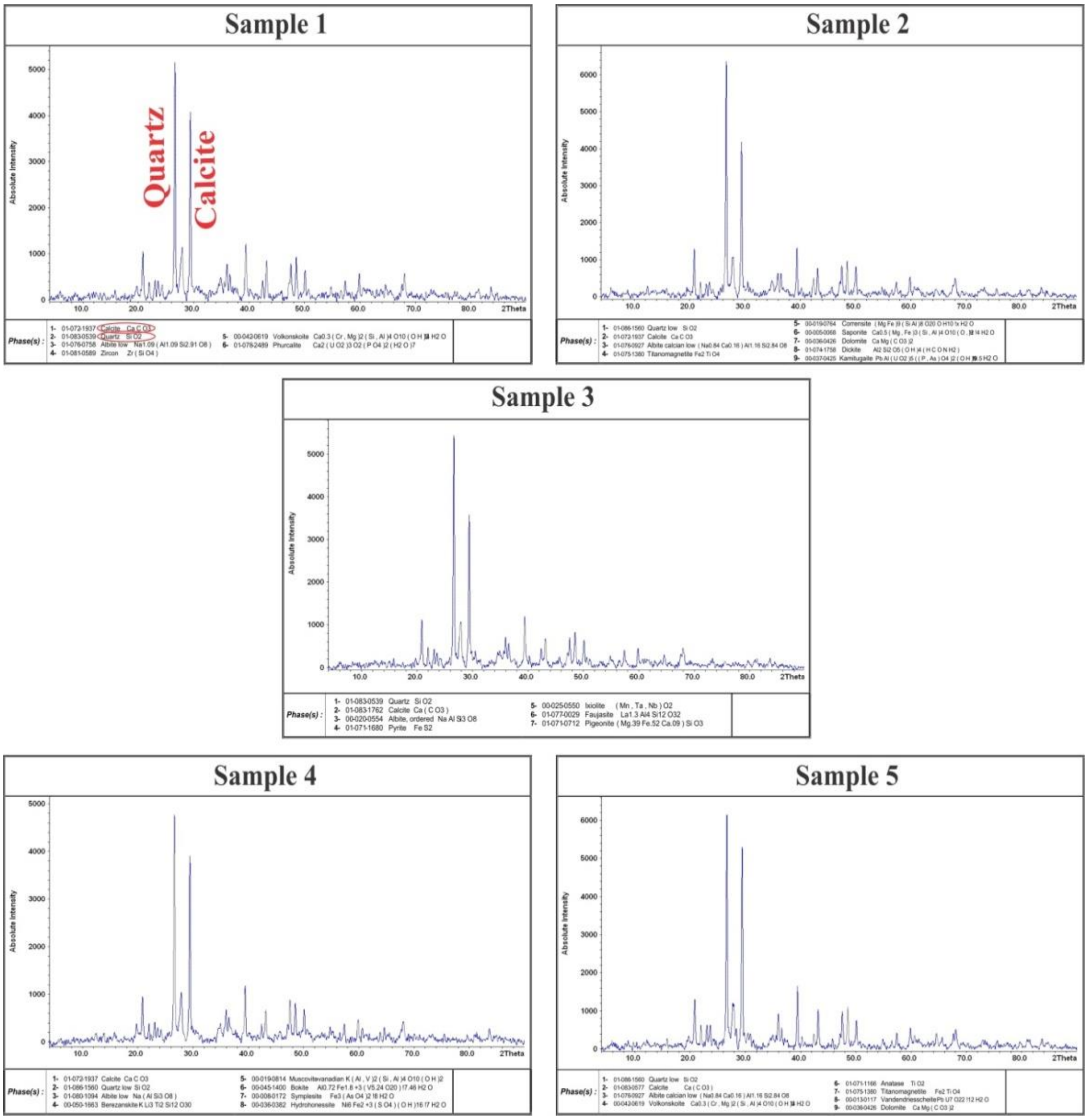


Figure 7. Diagrams obtained from the X-ray diffraction

4. Discussion

4-1. Characteristics of wind-blown sand dune sediments

The sediments within the Garmsar Desert dune fields exhibit broad regional homogeneity. These sediments are predominantly composed of medium-to-fine sands. As demonstrated by this study, characterizing sediment properties is crucial for estimating transport distances from sand sources. The analyzed sands possess mean and median grain sizes of 259.1 μm and 270.9 μm, respectively, which corresponds to the medium-to-fine sand fraction on the Wentworth scale. The minimal variance between these values suggests a consistent evolutionary history of the sediment particles within the dune complex (Wentworth, 1922).

The Garmsar Desert dune sediments display a unimodal grain-size distribution (Figure 4), with the modal peak consistently falling within the medium sand range for all samples. This unimodal distribution implies that the sediment is derived from limited sources, potentially a single primary source. In her studies of sand dunes in the Kuwaiti deserts, Khalaf found that the unimodal or bimodal distribution of sediment samples resulted from differences in the textural characteristics of the source sediments or the number of sand sources (Khalaf, 1989).The Strzelecki and Tirari Desert dune sediments exhibit a dominantly bimodal size distribution, with the larger modal peak falling within the sand-size range for all samples and the minor modal peak falling within the clay to fine silt-size range (Fitzsimmons *et al*., 2009).

Sorting coefficients range from 1.556 (medium-to-well sorted) to 1.779 (moderately sorted), indicating that the sediments are generally well-sorted within the medium-to-fine sand fraction (Table 2).Based on this coefficient, it can be stated that the sand source is not very far from the sand dunes.Benaafi concluded that the fine sorting of particles indicates a long distance from the sediment source areas (Benaafi *et al*., 2015).

Furthermore, the skewness values, ranging from strongly fine-skewed to moderately skewed, confirm the sorting processes across various particle size fractions. Similar to the sorting analysis, these skewness values further support the interpretation that the source of sand is not far from sand dunes.

As shown in Tables 1 and 2, the highest weight percentage of sediment falls within the 250 µm 500 µm range, which is indicative of a high-energy aeolian environment within the dune field.Analysis of wind energy environments and dunefield activity in Chinese deserts showed that sand dunes in most of these deserts are developed and controlled by low-energy wind regimes (Wang *et al*., 2005).

4-2. Location of sand resources

In the Garmsar region, there is a sand dune field with an area of about 670 hectares. The spatial distribution of sand dunes from the northwest (pre-barchan dunes) to the southeast (barchanoid and transverse dunes) indicates their evolution and maturity from the northwest to the southeast. Accordingly, the movement of new and young dunes is from the northwest to the southeast, and the progress of this complex is towards the northwest of the region, so the lands of the northwest are exposed to encroachment and occupation by sand dunes.

the study of the relationship between the form and elongation of the dunes and the direction of the prevailing and strong wind, showed that the direction of the strong wind is northwest (Figure 2 & 3). Therefore, based on the strong wind direction of the region, it can be concluded that the wind that creates and shapes the dunes is northwest-southeast and the sand sources or removal areas are in the northwest of the study area. Zhenda (1984) observed that in the Taklamakan Desert, sand dunes formed by prevailing northeasterly winds are aligned northwest–southeast, whereas those formed by northwesterly winds are aligned northeast–southwest.

Considering the diameter and mode of particles (Table 2), and the northwest-southeast direction of the erosive wind (Figure 3), sand sources in the removal sector can be located within a transport distance of 5 to 20 kilometers (Figure 8).

Based on the geological map and the extent of the removal sector, the following units are proposed as potential sediment sources for the Garmsar sand dunes:

Q^{al} ; River deposits alluvium. Q^{sd} ; Sand dunes. Q^{c} ; Clay flats with sodium sulfide. Q^{f2} ; Young gravel fan. Q^{t2} ; Young terraces and low level allovium. Q^{f1} ; Old gravel fan.

Three sources, Q^{f1}, Q^{al} and Q^{c}, from the saline ephemeral river (Shur River) washes draining the Kohe Sorkh Range provide the most sand for the dunes. (Khalaf, 1989). Similarly, Muhs *et al*. (2003) posit that Colorado River sediments have served as a important sediment source for at least three major dune fields within Analysis of the textural characteristics of aeolian deposits in Kuwait reveals that they are mostly derived from lower Mesopotamian muddy floodplain deposits, the sand fraction of the Al-Dibdibba gravelly deposits, and disintegrated material from calcretic and gypcretic duricrusts the Sonoran Desert of the southwestern United States and northwestern Mexico. Furthermore, Lancaster *et al*. (2012) observe that sand from the Keeler and Swansea dunes is much coarser and more poorly sorted than typical aeolian sands, suggesting that the sediment has not been transported very far from its source.

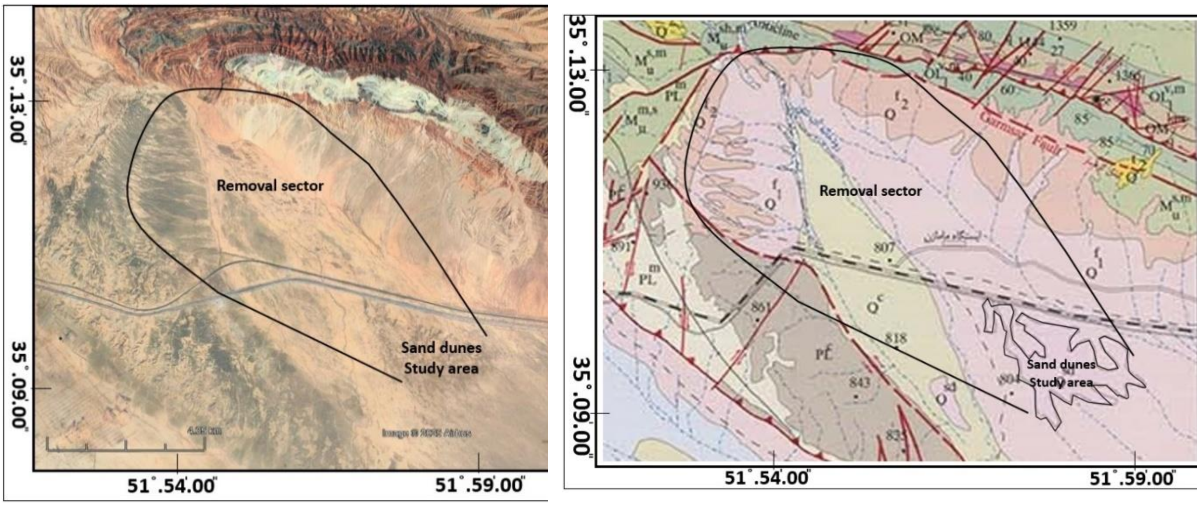


Figure 8. Removal sector in satellite images and geological map

4-3. Sand Origin

As previously noted, the primary mineral constituents of the analyzed samples are carbonate, quartz, and plagioclase, respectively (Figures 5 and 6). The plagioclases identified are predominantly sodic (albite and orthoclase). The volcanic fraction is characterized by a high SiO2 content, whereas the sedimentary fraction is dominated by CaCo3 (Figure 7).

The presence of relatively stable volcanic minerals (Figure 7) suggests that they have played a significant role in sediment generation within aquatic environments. It appears unlikely that wind-driven processes are responsible for the observed textural maturity, as stable minerals are typically susceptible to chemical weathering. Given the low annual precipitation in the study area, seasonal rivers likely serve as the primary agents for the degradation of unstable minerals. These minerals break down rapidly due to accelerated reaction rates in water; however, the duration of transport has apparently been insufficient to achieve significant textural sorting. It should be noted that the scarcity of unstable minerals might also reflect the composition of the source material; however, our conclusions are not based on this factor alone.

Upstream of the Shur River, the Upper Red Formation (URF) outcrops, consisting primarily of shale, siltstone, and sandstone. Furthermore, both the Qom Formation (calcareous marl) and the URF crop out along the river's course (Figure 9). Consequently, it can be inferred that the carbonate components originated from the Qom Formation, while the volcanic components were derived from the sandstone lithofacies of the URF. Observations from thin sections reveal that, in several instances, carbonate grains are either larger than or comparable in size to more resistant components like quartz. This suggests that the carbonate material from the Qom Formation was introduced along the river's path, having mixed with quartz-rich sediment already in transit from the headwaters. If all components had originated from a single source, a higher frequency and larger grain size of stable minerals would be expected; however, the fact that carbonate particles are occasionally larger supports the role of local riverine input. Alternatively, some sediment may have been sourced from gypsum and andesite units (containing quartz and plagioclase) within the Lower Red Formation at Takht Rostam Mountain. These materials were likely transported to the study area by the Khoshk-lat River after being initially deposited as aeolian sediments in the evaporitic flat (Figure 9). It is improbable that wind transport alone could move significant volumes of sand across a 10 km distance without the formation of extensive dune fields near the source. Moreover, the presence and relative grain size of the carbonate components provide further evidence for the dominant role of fluvial, rather than aeolian, transport.

The semi-quantitative mineral compositional data indicate that the sands are derived from granodioritic source rocks. Consequently, it is considered that the primary source of sand for the dune fields in the Owens Lake basin is sediment originating from the Sierra Nevada, transported via the Owens River from the north, as well as from granitic rocks in the Coso Range to the south (Lancaster *et al*., 2015).

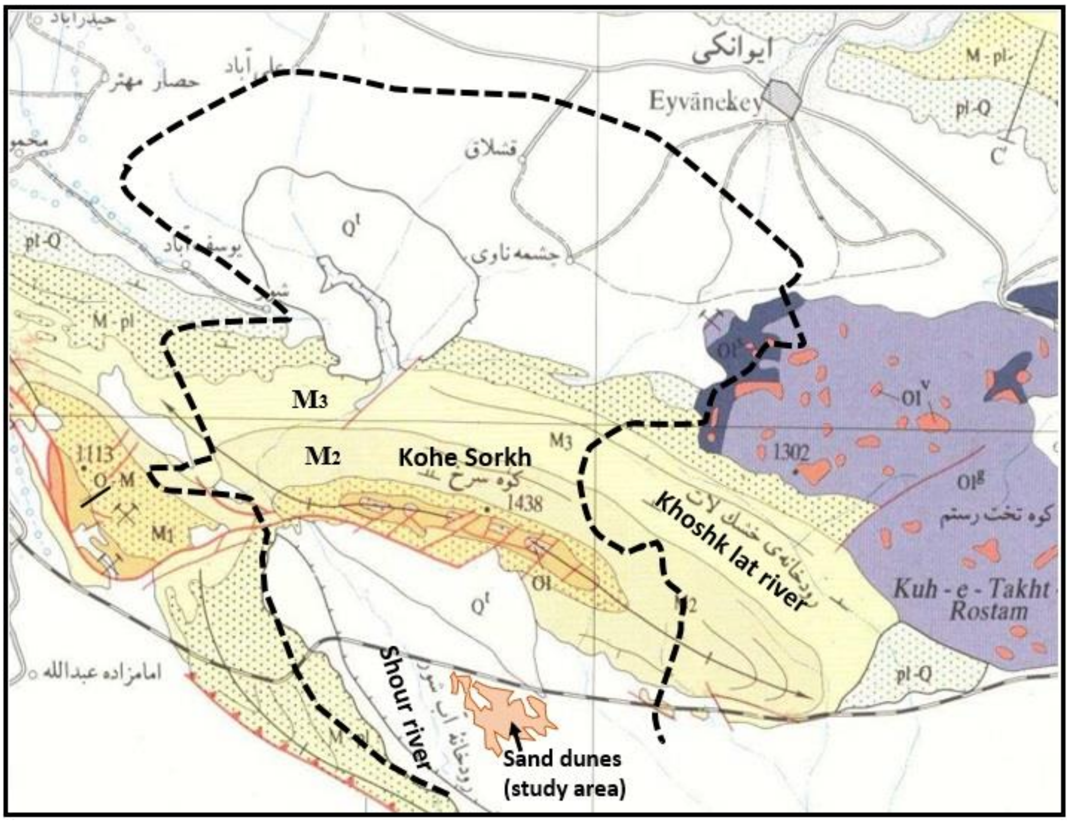


Figure 9. Location of sand dunes relative to lithological units within the watershed

4-4. Transport pathways

The transport pathways of the dune field, inferred from dune morphology, elongation, and storm-rose data, are schematically illustrated in Figure 10. The strong, prevailing north-westerly winds drive sand transport from the alluvial fans and clay flats toward the southeast. The resulting deposits range from simple crescentic to transverse dunes, which extend for approximately 4 km and cover an area of up to 670 ha.

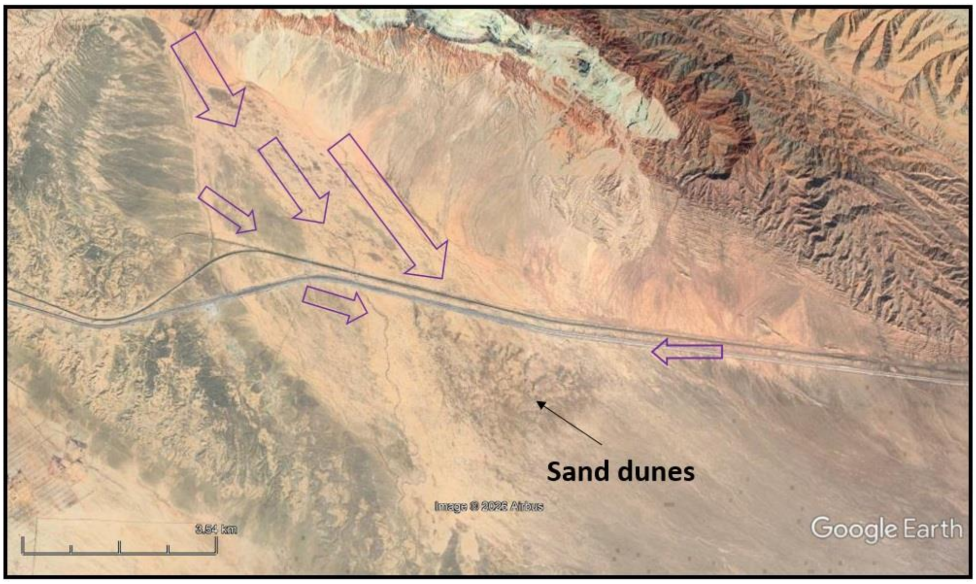


Figure 10. Schematic of sand transport pathways from sand sources. The size and volume of the flashes indicate the rate of sand supply. This figure shows the relationships between alluvial, fluvial, and aeolian transport.

Due to its ephemeral nature and declining water levels, the current discharge of the Shoor River has limited the sediment supply to the area. While a rapid expansion of the sand field is unlikely under these conditions, field observations suggest a slow northwestward progression of the dune field.Studies of the Parker dune field and the Yuma Desert have indicated that the aeolian sands likely originated from the Colorado River valley, rather than from local sources or by transport across the Colorado River from the eastern Mojave Desert (Muhs *et al.*, 2003).

5. Conclusion

The sedimentological characteristics of the Garmsar Desert dune fields, specifically regarding grain size and mineralogy, strongly indicate localized sand sourcing. Based on the compositional data obtained from this study, the following conclusions are drawn:

First, the Garmsar dune field is characterized by crescentic dunes oriented from northwest-west to southeast-east, implying that the dominant dune-forming winds originate from the northwest. Analysis of the aeolian sediments reveals that the primary sand source is situated in the northwest sector, approximately 5 to 20 km from the dune field, and includes sediment provided from the Kohe Sorkh (Red Mountain) through the system of ephemeral washes draining of Shur river (saline river).

Second, the dune sediments are quartz-rich, with subordinate amounts of plagioclase. The mineralogical assemblage is primarily composed of carbonate and volcanic particles. The carbonate fraction comprises intra-calcite and biocalcite, while the volcanic fraction consists of quartz and plagioclase—minerals that are chemically and physically stable under the prevailing environmental conditions.

Third, the ephemeral washes of the Shur River serve as the principal sediment conduit for the Garmsar dunes. These fluvial systems facilitate the transport of sediments by eroding the Upper Red Formation (contributing quartz and plagioclase) and the Qom Formation (contributing carbonate particles) along their course. A comparative analysis of stable (e.g., quartz) versus unstable (e.g., biocalcite) components suggests differential transport distances, indicating that these components have not been transported over equal distances by the riverine system.

In conclusion, these findings demonstrate that the major fluvial system (the Shur River) and its associated alluvial deposits play a critical role in the provenance and local sediment supply of the Garmsar Desert dune fields.

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Authors Contribution
Naser Mashhadi and Majid Karimpour: Conceptualization, Investigation, Methodology, Project administration, Supervision, Writing – review & editing. Davood Jahani, Yalda Mohammadi, Sirous Shamshiri: original draft, Laboratory operations, Investigation, Formal analysis, Data curation, Conceptualization.

Ethics approval and Consent to participate
The authors avoided from data fabrication and falsification.

Competing Interests
The authors declare that they have no conflicts of interest.

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Consent for Publication
The authors consent to the publication of identifiable details, which may include in-text details, which will be published in the journal and the above article.

Data Availability
Data available on request from the authors.

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